Trepanation, Trephining and Craniotomy

History and Stories

José M. González-Darder

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Preface

Virtually, all cultures over time have opened the skulls of its inhabitants, whatever the reason for it. In primitive or prehistoric cultures, where there are no written records, it is not possible to know with certainty the reasons for this practice. Therefore, almost everything is speculative in this field. In historical cultures, with written records, it is possible to know the reasons, techniques, and fundamentals of this action. The trepanation, trephine, and craniotomy are no more than different forms of cranial opening. The universal human interests that justify this cranial opening along the time may be of a predominantly magical, empirical, or scientific nature. Interest and justification have been changing over time. For centuries, trepanation was itself a treatment that pursued the removal of fracture lines in the skull. Later, the small cranial opening achieved with the trepan or trephine allowed the evacuation of collections located under the bone. Finally, modern craniotomy has become the gateway to the intracranial space, the place where the human anatomy is more complex, delicate, and sensitive and where the neurosurgeon's preferred and exclusive workplace is. In this book, we travel this long road with the aim of writing the first complete and comprehensive history of the cranial opening techniques over time.

This book is the first treaty that addresses this issue with this particular objective. It stands out the cranial opening technique and the instruments dedicated to it over time. We highlight the authors who have contributed innovation to the technical aspects of the cranial opening and the necessary instruments for this. This information is contextualized for a better understanding of the circumstances that require technical improvements and innovations. We highlight the techniques and instruments of success in each period of time and the causes of the failure of designs that eventually failed to flourish. This vast extension of the subject prevents that it has been possible to deepen or investigate in many obscure aspects of the history of the cranial opening.

Every historical study requires a series of conventions. One of them refers to the compulsory division into stages or chapters. Based on cranial opening techniques, we have divided our study into three extensive periods of time linked to the different trepanation, trephine, and craniotomy techniques. Another convention is to assume by the author a personal vision of each of these stages based only on historiographic data. Other conventions are of semantic type or related with the particular cultural view of the author linked with his personal cultural heritage.

Nowadays, the abundant documentary and iconographic information available in the bibliographic repertoires allow an in-depth study of the history of the evolution of the cranial opening. In this sense, we must thank the libraries and directories for the free disposal of these bibliographic funds, nowadays, as public domain resources and easily available in the Internet. Many of these entities have provided high-quality figures for reproduction in this book. By far, the most splendid and generous collaboration has been received from José María Fernández Díaz-Formentí, who has made available to us a superb collection of photographs of trepanned Peruvian skulls. All the images are of great technical and artistic quality, as well as of great scientific value. Others have helped in the labor of organizing the work. I also want to highlight the job of Aurea García, who did the important work of translating the first original text written in Spanish into English. The researcher intensely enjoys the time spent studying a topic and loses the notion of the time that passes. This time is subtracted from the relationship with his closest people. Dolores is the one who has graciously yielded this time to be the author able to write his work, and it is fair to thank her.

Modern craniotomy is the essential surgical technique in Neurosurgery and the one that is the core of this surgical specialty. Knowing the history of every subject is necessary to better understand what is done and what will be done in the future. Therefore, neurosurgeons from around the world can better understand the place they occupy nowadays in the general history of the Medicine and Neurosurgery by reading this book. In the same way, people interested in the development of medical science can increase their knowledge in a seemingly marginal topic, but that follows the general principles of the history of Medicine. Cranial opening can be followed as a case problem. All people interested in the history and the histories of the medical culture can enjoy and evoke past times through by reading this work and, in particular, of the illustrative cases selected.

Valencia, Spain José M. González-Darder

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1 An Overview

At this very moment, or actually at any moment of the day, a lot of neurosurgical interventions that require the patient's cranium to be opened are being performed anywhere around the world. Opening the cranium, just like it is nowadays done with slight variations by neurosurgeons worldwide, is the final result of a great amount of efforts, improvements, solutions and scientific, technical and technological innovations that innumerable surgeons, manufacturers and engineers have provided throughout history. This book reviews the history of all this process, which includes the different geographical, historical and cultural arenas as well as those related to the medical and scientific knowledge. They all need to be assessed and contextualised.

Historically, trepanation, trephine and craniotomy have been the basic methods of cranial opening. Taken out of the neurosurgical field, the term 'trepanation' is immediately associated with an almost ancestral image. Some people will link it to the prehistoric trepanned skulls found in Europe that belong to the Neolithic period. Others bring to their minds the pre-Columbian trepanned skulls found in the Peruvian or Bolivian Andes. From an etymological point of view, the term trepanation only means perforating the bone, preferably the skull, and it does not take into consideration the size, technique or purpose for that action. According to this, any type of perforation or surgical cranial opening can be considered as a trepanation. The cranial openings of our ancestors that were found in the exhumed skulls from the archaeological sites show very different sizes and shapes. Many of them are simple, small and circular holes that resemble modern burr holes. In many other cases, the ancestral skulls show surprisingly big openings or apertures, with several square centimetres. Sometimes old trepanned skulls have almost perfect circular holes with a diameter of several centimetres, an intermediate size between the burr hole and the craniotomy.

1.1 Historical and Geographical Scenarios

The second half of the nineteenth century is a key moment in the history of cranial opening. The first milestone and determining factor is related with the ancestral trepanations. It was the discovery in 1865 of a trepanned pre-Columbian skull by Ephraim G. Squier (1821–1888) in Peru, which was studied in Paris by Paul Broca (1824–1880) [1]. This triggered the scientific interest on European and pre-Columbian ancestral trepanations, which spread among erudite scientists to other primitive cultures later. The second milestone was the launching of the craniotomy. It was the description made by Wilhelm Wagner (1848–1900), 30 years later, in 1889, of the first comprehensive cranial approach designed with the aim of performing a surgical therapeutic action in the

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intracranial space [2]. Wagner named this approach a 'temporary cranial resection' and can be considered as the origin of the modern craniotomy. Wagner's original craniotomy is a technical development of European medicine and means a paradigm shift in the cranial opening techniques. From that moment on the technique of craniotomy developed as a neurosurgical solution to the intracranial pathology approach. However, until that moment European surgeons used to perform trepanations. What was the situation of the cranial opening techniques in Western medicine before the craniotomy then? How did those trepanation techniques come into being? And how was their development until that historical moment?

European and American scientists of the end of the nineteenth century were astonished by the size, amount and quality of the ancestral trepanations from the Neolithic and pre-Columbian periods, which were just brought to light in that time. The first response in many scientific societies of that time was to deny reality and associated them with environmental factors, postmortem actions or a possible fraud. Thanks to Paul Broca it was widely accepted that the trepanations found in the skulls had been performed in live individuals and that they had survived the trepanation. This feeling of excitement and admiration still persists and it is undeniable even for a modern neurosurgeon when he or she looks at a trepanned Neolithic or pre-Columbian skull at a museum.

In the nineteenth century the trepanations performed by surgeons of that time had indeed a smaller size; they were also surprisingly scarce except for war surgery and showed less technical quality than the ancestral ones. To make it worse, patients had a lower probability of survival than the trepanned individuals whose skulls were exhumed from archaeological sites, as the latter were supposed to have a very high survival rate at that moment.

However, we must keep in mind that by the end of the nineteenth century surgeons had already developed specific instruments for surgical trepanations with drills, saws and trephines. By that time the indications and the techniques to trepan had also been described and were gathered in detail in treatises and texts on surgery. This confirms that, although they were limited, small and clumsy, surgeons knew how to perform trepanations and eventually carried them out. This process had started centuries before.

Also, centuries before, in another historical and geographical context, Spanish physicians and surgeons of the sixteenth century were not aware of the fact that in the Inca populations that had been discovered, conquered and become civilised a great amount of sophisticated cranial openings were performed with a high survival rate. Actually, there are no references in the Spanish chronicles of the conquest about this practice. Nevertheless, in that historical moment trepanations were also performed in Spain and in Europe according to a great amount of indications, techniques and instruments that are described in the medical treatises of that time. A handful of historical references that are well documented and that particularly affect kings and people belonging to the nobility or the court show that trepanation was a well-known practice that surgeons who were often trained on war surgery regularly performed.

By that time, scientific fundamentals of medicine, and particularly anything related to trepanations, were based on the *'Corpus Hippocraticum'*, a collection of some 50 works attributed to the Greek Hippocrates of Kos (460–337 BC) and whose originals are not preserved [3]. These texts experienced the different vicissitudes of history and successive handwritten copies were made, translated and probably modified. However, it is wonderfully surprising that the techniques, indications and instruments for the trepanations that are described in the Hippocratic texts are almost comparable to those described and used by the authors of the European Renaissance, like the Spaniard surgeons in America, and that only a handful of modifications or new contributions were added to the medical descriptions made before the nineteenth century, when the ancestral trepanations were brought to light. However, this is very important from a historical point of view as it proves the existence of a link chain that safely paves the way so that modern craniotomy can be considered the final result of the development of the basis of trepanation that was implemented in the Hippocratic texts.

Unluckily this retrospective historical clue vanishes when we try to find information about the foundations on which the authors of the *'Corpus Hippocraticum'* in turn based to describe in such a precise way the knowledge on trepanations. These foundations, of course, must have been based on the previous expertise. The lack of documents or archaeological remains makes us venture into a speculative territory which could take us, in any case, to the primitive pre-Hellenistic civilisations and, following this way, back to the European Neolithic trepanation.

Therefore, after this quick journey over the trepanation and craniotomy, we can recognise several scenarios where the cranial opening techniques have been developed. Although there are many geographical, cultural and chronological vicissitudes, we can find one core element that is common and connects both the Neolithic and pre-Columbian primitive trepanations. In both cases, they were activities that were carried out within prehistoric cultures; that is, they were developed in a geographical territory and in a period of time that was previous to any written document. These civilisations and cultures are only known by means of certain remains, such as buildings, instruments and human or animal bones. This aspect is essential because, in addition, the remains related to trepanations are scarce. Actually, they are almost restricted to cranial remains. Unfortunately, the existing evidences are not enough to let us reconstruct a sound framework that explains all the circumstances involved in trepanations.

The oldest primitive trepanations refer to a geographical area restricted to Europe, specifically around the Mediterranean Sea, and covered the Neolithic, which started 5000 years BC. This period coincides in Europe with the emergence of agriculture and dies with the introduction of bronze metallurgy (about 2000 years BC). That means it lasted about 3000 years. The trepanations carried out by the American pre-Columbian peoples refer to different Andean cultures, particularly from South and Central America, which existed during many centuries but ended abruptly after the Spanish conquest, that is, at the beginning of the sixteenth century. Leaving the fictitious theories apart, the evident impossibility of communication between both scenes shows us one of the first elements that characterise primitive trepanations: their presence worldwide anytime.

Surprisingly, the general model of these types of Neolithic and pre-Columbian trepanations is repeated in other geographical and chronological fields. Later on, we will see how different primitive cultures located in different places and from different chronological periods, who had no possible connection between them, performed trepanations with a similar fashion, using similar techniques and apparently sharing the same purposes. Trepanations have been carried out by prehistoric cultures and throughout history, even in almost contemporary times and in many places of the world. They have been discovered thanks to archaeological remains. Additionally, there is documentary and even iconographic information on trepanations that were performed in very recent times within primitive Berber cultures from the North of Africa, Polynesian islands and black tribes from Central Africa, such as the '*kisii*' tribe from Kenya. All these trepanations carried out by prehistoric or primitive cultures have elements in common and make up the first historical scenario for the study of trepanations.

The second scenario is the long saga of trepanations since their documentary description in the Hippocratic texts until the modern craniotomy introduced by Wilhelm Wagner. It is a long period of time of more than 2000 years in which the practice of trepanation and the historiographical traces thereof experienced the historical and cultural vicissitudes of the civilisations in which they were carried out. During this period there are documentary and archaeological elements that allow us to track the evolution of trepanations, showing thus that there is a historical continuity. Although there have been dark periods of time, we can affirm that there is no reinvention of the trepanation but a common thread that has always been present. This historical period could be divided in turn into two acts, just like a theatre play.

The Hippocratic texts are the first documentary elements in which the practice of cranial opening is described along with many other medical practices. These handwritten texts, of which the originals are not preserved, experienced innumerable difficulties. Each modification, whether it was just a transcription or a complex translation, was reflected in a new handwritten document that constantly accumulated errors, oversights, changes, contributions, interpretations and other alterations that unavoidably modified the original text. The problem caused by both losing or altering the information contained in the original and widely spreading it throughout the geographical field and time only started to ease with the generalisation of the printing press in the second half of the fifteenth century. In this way, the Hippocratic texts were printed in Latin for the first time in Rome in 1525 and in Greek in Venice a year after, in 1526. Also, in the second half of the sixteenth century, the doctors at that time, who became filled with the pertinent Renaissance scientific spirit, started publishing large treatises on medicine and surgery, in which they described the techniques of trepanation and for the first time included illustrations of the used instruments.

Later on, scientific and particularly medical knowledge and information increased and influenced the trepanations. As it was a sporadic technical and specialised action, the interest thereon was probably not great and very little conceptual improvements were made, as well as in the surgical instruments. The eighteenth century brought a very important historical change: the emergence of science and American scientists in all fields and particularly in Medicine, which had been until then a European heritage. It will be mainly based on Anglo-Saxon ideas and postulates. In the case of trepanations, two different technical styles can be recognised since then. The European one focused on French surgeons and the British one, which was located at both sides of the Atlantic Ocean, which experienced a particular development of the trepanation techniques in America due to the bloody American Civil War (1861–1865).

Therefore, we can split this historical period into two different episodes. The first one starts with the Hippocratic texts and extends until the initial Renaissance with the first printed medical texts that were published in Latin. In geographical terms, it was initially developed in the Mediterranean basin and later spread to Europe. The second one covers a period until the end of the nineteenth century, when modern neurosurgery was born. In the case of the cranial opening techniques we relate this historical moment with Wagner's first description of the original craniotomy. The geographical locations of this second period exceed the European borders and start a phase that we currently call globalisation, as trepanation spreads worldwide along with the overseas processes of colonisation of the European countries.

Finally, the third scenario is completely different. It is based on the cranial opening within the modern neurosurgery field and starts with the description made by Wilhelm Wagner in 1889 of the very first craniotomy. We can assume that this is the ancestor of the current craniotomy. It is a short historical period of about 130 years that is well documented and allows us to track the conceptual, scientific, medical and technological evolution of craniotomy. Accordingly to this historical period, the leading aspect is the technical evolution applied to the cranial opening and how the technological changes become more and more important and quick. The current techniques of cranial opening do not mark the end of the road, but a temporary situation of a continuous improvement process that is relentlessly being carried out by multiple contributions and enhancements that may (or not) have medical, business or commercial success and if so they end up being applied to the neurosurgical practice.

1.2 General Structure of the Book

There is no book that reviews the techniques of skull opening over time and in the different geographical areas where it has been carried out, from the Neolithic trepanations to the present.

The book edited by Arnot, Finger and Smith in 2003 brings together different papers on the subject written by different authors [4]. The review is not exhaustive and many issues remain unchecked or are treated unevenly. Chapters written by different authors make that the global vision on the subject is lost. The authors have very high scientific standards, but very few have neurosurgical training. The topic of the craniotomy is not reviewed. Even in spite of the aforementioned, it is the only book that comprehensively addresses the issue of cranial trepanation throughout the ages and cultures.

Other authors also review the topic, although as part of general treaties of cranial surgery, particularly in the late nineteenth century [5–7]. Other similar reviews refer to the history of neurosurgery, where the question of a cranial opening is addressed tangentially [8–10]. Louis Bakay, a neurological surgeon, wrote in 1985 a short book entitled *'An early history of craniotomy'*, which reviews the techniques of cranial opening and the history of the neurosurgery until the early nineteenth century [11]. This lack of a general history of the cranial opening is solved with this book.

Now we are going to detail how the book has been organised so that it can be easily understood. The following chapter describes the cranial trepanation technique used within different primitive civilisations. We prefer the term 'primitive' rather than 'prehistoric', which is more used. The term prehistoric means indeed the period of the history of mankind, and thus the history of any society, culture or social organisation, which was previous to the emergence of writing, which allows to obtain from its documentary information about the issue that is the object of the study. With the term 'primitive' we mean any culture or civilisation that was poorly developed, normally had no writing remains and left more or less comprehensive archaeological information. However, according to the available data it is observed that they lacked a scientific reasoning system and thus the consequences thereof on technologies and beliefs. This allows us to include in this chapter the trepanations performed by some groups culturally primitive, which are almost contemporaneous in time. It has been possible to obtain documentary information directly from these groups, even by means of interviews, direct visualisation of the trepanations and also photographs and films. All these primitive civilisations ended up vanishing or collapsing after a more or less extended geographical expansion and a fairly long historical trajectory. As it has been established, the core element of the trepanation within primitive cultures is the magic-religious aspect. We might consider an empirical component but there is no sign of a medical scientific basis in their actions.

We will later describe the evolution of the trepanation initiated in Greece, which was documented in the book entitled *'On Wounds of the Head'* that belongs to the *'Corpus Hippocraticum'*. By reading this text we can rapidly recognise the elements that let us clearly differentiate this sort of trepanation from the one performed by primitive cultures. The first fact consists of the absence of any magic-religious component in the description of the procedure as the trepanation is suggested as a solution or treatment for an underlying, supposed or evident cranial or intracranial pathology, describing thus the clinical methods to identify and solve it. The *'Corpus Hippocraticum'* is actually the first medical text in which it is possible to recognise a medical technique or procedure as well as the people within society that have the knowledge to perform it. Another differential trait is that there is a written documentary record, although it consists of copies of original texts that were lost shortly after they were written, along with a certain amount of archaeological remains and instruments. This record can be traced reliably until the end of the nineteenth century, when craniotomy was irrupted. As we said, this long period of time has been artificially divided into two stages. The first one covers until the sixteenth century, when the first printed medical texts from the Renaissance appeared. The second one extends until the end of the nineteenth century, when trepanation was rapidly substituted by craniotomy.

Afterwards, the real history of craniotomy starts. This is the neurosurgical intervention that is exclusive and characteristic of modern neurosurgery. From its beginnings, craniotomy has been a technique that completely lacked any magic-religious component and in which the empiric element had a minor role. Actually, the modern craniotomy turns indeed into a part of the neurosurgical procedure to solve the intracranial pathology and in most of the cases is set aside just for the approach. For this reason, it has a separate evolution from the paradigm shifts in neurosurgical treatments for intracranial pathology and its developments are mainly of a technological nature.

Finally, at the end of each chapter, we collect a large number of original illustrations of the instruments used for trepanation taken from medical and surgical texts reviewed in our work. Comments and translations are also included to understand the illustrations. Some beautiful sheets of trepanation techniques are also reproduced. These illustrations serve as a complement to follow the text and show the evolution of techniques and instruments over time.

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2 Semantic Features

The problem that arises from defining and translating medical terms among different languages, and particularly the techniques and surgical instruments, is extremely important in historic books on medicine and, therefore, in this book. Regarding the correct use of words, we must take into consideration their meaning and etymology.

In English the words 'semantic' and 'etymology' have an easily understanding meaning. Semantic is defined by the Oxford Dictionary as *'relating to meaning in language or logic'* and etymology as *'1. The study of the origin of words and the way in which their meanings have changed throughout history'* and *'2. The origin of a word and the historical development of its meaning'*. In other languages like Spanish, due to the same etymological origin of these words, the meaning is almost the same. The dictionary of the Real Academia Española de la Lengua defines *'semantica'* as follows: *'Del gr. σημαντικός sēmantikós 'significativo'* (From Gr. σημαντικός sēmantikós, 'meaningful'). *1. adj. Perteneciente o relativo a la semántica* (Belonging or related to the semantic field). *2. f. Significado de una unidad lingüística* (Meaning of a linguistic unit). *3. f. Ling. Disciplina que estudia el significado de las unidades lingüísticas y de sus combinaciones'* (discipline in charge of studying the meaning of the linguistic units and their combinations). The same dictionary defines *'etimología'* as follows: *'Del lat. etymologĭa, y este del gr. ἐτυμολογία* etymología (From Lat. etymologĭa, which in turn comes from the Greek word ἐτυμολογία etymología). *1. f. Origen de las palabras, razón de su existencia, de su significación y de su forma* (Origin of words, reason for their existence, their meaning and their form). *2. f. Especialidad lingüística que estudia la etimología de las palabras* (Field of Linguistics that studies the etymology of words)'.

In the best-case scenario, the words we use to describe the old techniques and instruments in contemporary languages are usually the result of a translation made in the nineteenth century from Latin into modern languages of the words that, in turn, the Renaissance translators chose to translate from the by then available texts in Greek, Arabic or Hebrew into Latin. Translating a text long after it was written by its author poses severe semantic problems for translators. Among the translation procedures that can introduce mistakes we can include transliterations, periphrases of different types, univocality or using adjectives instead of nouns. This topic departs from the purpose of this work but we must take it into account when it comes to reading and using certain terms.

We can use as an example the reflections presented by the Spanish researcher P. Conde Parrado about the four translations of Pablo de Egina's volume VI (*'Liber VI De re medica'*), focused on surgery, which were carried out by four different translators in the sixteenth century [1]. The author studies the problems derived from the translation of the more than 50 surgical

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instruments that appeared in the original Pablo de Egina's work, which was written in Greek and the names assigned in Latin by the four different translators. As extreme examples, he focuses on the Latin word *'acus'*, which means 'needle'. This word shows correspondence between all the Latin translations and the Greek original. On the contrary, the Latin term *'scalpellus'* (which means 'scalpel') used by the translators almost never corresponds with any other Greek term written by Pablo de Egina. This shows a real overuse of this term in the Latin translations studied. We must assume that a problem like this was repeated when these Latin translations were in turn translated into living languages of the time shortly after and in subsequent translations, especially those carried out by the end of the nineteenth century.

To solve these problems many medical works from the Renaissance that were written for the first time in vernacular languages include glossaries with medical words and terms and their equivalents in Greek, Latin and, at least, the vernacular language in which they were written. This problem is so real that many authors allude to it at the beginning of their works. Hans von Gersdorff (1455?–1529) was the first one who wrote a medical text in German in 1517, the *'Feldtbuch der Wundarzney',* which already includes at the end three Latin-German glossaries on anatomy (*'Vocabularius Anatomie'*), pathology (*'Vocabularius infirmitatum'*) and herbalism (*'Vocabularius herbarum'*). According to this, we can confirm that by then there was already a need for being very specific in semantic aspects in the medical field. The *'Vocabularius Anatomie'* is a short glossary of descriptive terms relating to human limbs and organs aimed at barbers and surgeons, who unlike doctors did not speak Latin but needed to understand and use Latin terminology. It sometimes introduces Greek and Arabic terms, showing a great number of mistakes. Generally, there is single, double or multiple direct translations but there are anatomical terms that are described or paraphrased. For instance, the dura mater is explained this way: *'dura mater. vsszer grob hirnfell'* (dura mater. vsszer roughly brain-fur). In other cases, the translation is accompanied by an explicative description or a clarifying example. The same strategies are used in the two other glossaries. Von Gersdorff's *'Adendum'*, which contains a total amount of 316 entries, is an impressive etymological and lexicographical work [2].

During the same period Jacopo Berengario (1457–1530) described in his book *'Tractatus de Fractura Calvae sive Cranei'*, which was published in Latin in 1518, the instruments used in trepanations [3]. He specifically wrote that *'instruments are named in so many different ways that sometimes those who hear these names are confused'*. This is why he put the name of each instrument beside each image and admitted the need for a list or some kind of index thereof. This rule was followed at that time by a great number of authors in their works and the names of the illustrated instruments were written near them.

Later on, Laurent Joubert (1529–1582) came back to this issue in his book *'Annotations de M. Laurens Ioubert, sur toute La Chirurgie de M. Guy de Chauliac'*; the title is followed by the sentence *'avec l'interprétation des langues dudit Guy: (c'est à dire, L'explications de les termes plus obscurs) divisé en quatre classes: chacune estant rangée selon l'ordre de l'Alphabet'* (With the interpretation of the languages of the said Guy: [that is, the explanations of the more obscure terms] divided into four classes: each being arranged according to the order of the Alphabet) [4]. The author includes the interpretations of the terms used by Guy de Chauliac (c1300–1368) in the work *'Chirurgia Magna'*, which was published in Latin in 1363 and gathers them in groups of anatomical, pathological, pharmaceutical and surgical terms. He explains the meaning of each term and its correspondent in classical languages, i.e. Greek, Latin and Arabic, and in barbarian or modern languages, such as French and Spanish. For example, Joubert draws in his book a series of bone- and skull-piercing instruments, named as follows: *'Tariere ou Terriee: en grec Trypane, le vulgaire dis Trepan signifie un foret ou villebrequin: c'est en Latin terebra & terebellium'*.

The problem persists over the centuries. A good example of this is offered by the Spanish historian Víctor Escribano-García (1870–1960), who specifically wrote in his study on the trepanned skull of Enrique I of Castile in 1949: *'de aquí la presente obscuridad y confusión de palabras y conceptos que convendría corregir rectificando el lenguaje quirúrgico, un tanto arbitrario, de libros antiguos y modernos en este capítulo de la cirugía de la cabeza, con definiciones claras de nombres y verbos, como por ejemplo: trépano, trefina, terebelo, taladro, perforador, barreno, tirafondos, craneotomía, craneoplastia, trepanar, horadar, perforar, taladrar, penetrar, agujerear, trabajo entretenido y ya hoy de pura curiosidad histórica y acaso de ninguna utilidad práctica puesto que ha cambiado fundamentalmente ese capítulo, desde la Edad Media hasta nuestros días, en cuanto a la exploración y diagnóstico, a las indicaciones quirúrgicas, al instrumental y a los modos y fines de la maravillosa operatoria endocraneana contemporánea, tan digna de alabanza y de admiración'* (Hence the existing darkness and confusion of words and concepts that would be advisable to solve by rectifying the surgical language, which is quite arbitrary, of old and modern books in this chapter on head surgery with clear definitions of nouns and verbs, such as: trepan, trephine, terebellum, drill, borer, borehole, lag bolts, craniotomy, cranioplasty, to trepan, to bore, to perforate, to drill, to penetrate, to pierce. This is a time-consuming work based on pure historical curiosity but with no practical value because that chapter has dramatically changed the surgical indications, the instruments and the methodology and aims of the contemporary and so worthy of praise and admiration intracranial operative technique from the Middle Ages until the present day in terms of exploration and diagnosis) [5].

Most of the ancient books written or translated to Latin have never been translated to modern languages despite the outstanding longevity of their use among surgeons. The meaning of anatomic or neurological terms and pathological conditions has been different from what we use today. A real problem is that late translations of old medical texts introduce words that were created after the originals were written, that is, neologisms. We are probably going to use this licence unintentionally in this work. It is clear that the list of surgical instruments is different in each given time and it is becoming more comprehensive over time. Thus, it is easy for the translator to employ contemporary nouns to describe old instruments according to their modern use or physical similarities. This way, the old instrument is related to a current word so that the reader of this time can easily understand it. These modifications could repeat in subsequent translations, worsening thus the problem. The consequence is that the reader of the last version of the text has the feeling that those neologisms were actually words used by the author in the original work. And worst, the reader can think that current surgical instruments were real and in use by ancient surgeons because they are named in the translations with modern terms.

As we have already mentioned, the three most important cranial opening techniques over history have been trepanation, trephine and craniotomy. Their etymological and linguistic aspects will be discussed later. There are also some surgical instruments to which the same considerations can be applied, such as the trepan itself and the trephine, along with others of less importance, like the instruments for cleaning the bone and handling the osseous fragments. We will also explain the latter in future pages.

2.1 Trepanation

From an etymological point of view, the term trepanation only means perforating the bone, preferably the skull, and it does not take into consideration the size, technique or purpose for that action. The English definition of 'trepan' by the Oxford Dictionary is as follows: *'NOUN. 1) Historical. A trephine (hole saw) used by surgeons for perforating the skull. 2) A borer for sinking shafts. VERB. Perforate (a person's skull) with a trepan'*. More specifically, in Spanish the Real Academia de la Lengua Española (Royal Academy for Spanish Language) defines *'trepanación'* as action and effect of trepanning *('f. Med. Acción y efecto de trepanar')*; 'to trepan' is defined as to perforate the cranium or other bone with a healing or diagnostic purpose *('tr. Med. Horadar el cráneo u otro hueso con fin curativo o diagnóstico')*; and finally, 'trepan' is defined as the instrument used for trepanning *('m. Med. Instrumento que se usa para trepanar')*. The French dictionary Larousse defines *'trépan'* as '*nom masculin (latin médiéval trepanum, du grec trupanon). Instrument chirurgical en forme de foret permettant la réalisation d'un orifice dans un os, essentiellement la boîte crânienne'*. According to this, any type of perforation or surgical cranial opening can be considered as a trepanation. However, in the current neurosurgical practice the term trepanation is seldom used, especially with the generic etymological meaning that was previously defined.

The cranial openings show very different sizes depending on their purpose. Many of them are simple, small and circular holes that we name nowadays as burr holes. The term 'burr hole' is used when we refer to a perforation of a small, circular hole, generally with a diameter of less than 1–2 cm, in the skull. It is normally performed with a drill or a burr with a rotation movement that is manually driven or has a pneumatic or electric-powered motor, obtaining bone sawdust.

In many other cases, we found big openings or apertures, with several square centimetres. In the current neurosurgical practice, we generically call 'craniotomy' those big-sized cranial openings. Craniotomy is a modern surgical technique that was born at the end of the nineteenth century to solve the challenges of cranial approach posed by modern scientific neurosurgery. It was then when the use of that term started. Interestingly, the word *'craneotomía'* is not included in the dictionary of the Real Academia de la Lengua Española, whereas 'craniotomy' is accurately well defined in English in the Oxford Dictionary as follows: *'NOUN. Surgical removal of a portion of the skull'*. The current neurosurgical use of the word craniotomy specifically refers to the cranial opening or window which has a big size and variable shape and that has been obtained after making one or several burr holes and cutting linearly the bone existing between them. We normally obtain one single osseous piece that can be reused afterwards if we want to cover with it the osseous window that has been made on the skull.

Sometimes trepanned skulls have almost perfect circular holes with a diameter of several centimetres, an intermediate size between the burr hole and the craniotomy. One way of obtaining these circular holes and with such relatively big size can be by means of an instrument called 'trephine'. The term *'trefina'* does not appear in the dictionary of the Real Academia de la Lengua Española either, but it does in the Oxford Dictionary, where it is defined as follows: '*NOUN. A hole saw used in surgery to remove a circle of tissue or bone. VERB. Operate on with a trephine'*. The neurosurgical use of this term refers to a hole with a bigger size than a burr hole and that is performed on the skull by rotating a cylindrical hollow instrument that has a serrated edge, also known as trephine, obtaining thus a perfect circle from the bone. Historically, the surgical use of trephine as a cranial opening system in skull surgery had its golden age until the end of the nineteenth century. Afterwards it has always been a secondary method of trepanation regarding burr holes and craniotomy. Nowadays, it's almost abandoned. The term trephine was also introduced very late, starting from the seventeenth century, and the origin of this word is unsure and will be discussed later in this book.

Although burr holes, trephines and craniotomies are actually types of cranial trepanation, those terms must be used properly and can't be used interchangeably. Therefore, we advocate that all of those old cranial openings, even the biggest ones, should still be named trepanations. This is how it is normally done in modern literature on this issue. In this book, any type of cranial opening made before modern craniotomy was introduced should be generically called trepanation, including both prehistoric cranial openings and those made by the surgeons before modern craniotomies were performed.

2.2 Trepan and Trephine

The current neurosurgical meanings of the terms trepan and trephine are the following. A trepan is a small hole made on the skull by perforating with a burr or a drill (trepan), producing bone sawdust. A trephine is a larger hole on the skull that is made by rotating a cylindrical hollow instrument that has a saw on its free edge, called trephine. Once the perforation is over, a perfect disc of bone is obtained.

The different meaning that we nowadays give to these different types of cranial perforations was not so clear throughout history. Unfortunately, the use and meaning of the terms 'trepan' and 'trephine' have changed over the centuries and they have also had different meanings for different authors and in different languages. We can affirm that the term trepan (in Latin *'terebra'*, from Greek language *'trupanon'*) was used by ancient authors to refer to an instrument used for making cranial drills with a small diameter. The *'modiolus'* was the tool used for making larger drills with a perforation element that was similar to modern trephine crowns. Curiously, the word *'modiolus'* disappeared from the medical texts from the seventeenth century onward as it was substituted by the word trephine.

The term 'trephine' is included in the prestigious Oxford Dictionary. It is accurately defined as follows: *'Trephine: A hole saw used in surgery to remove a circle of tissue or bone'*. Equivalent terms are used in Spanish (trefina), French (tréphine), German (Trephine) as well as Italian (trephine) and Portuguese (trephina). However, the term *'trefina'* is not defined in the Dictionary of the Real Academia de la Lengua Española (Royal Academy for Spanish Language).

The meaning and use of the term trephine raise interesting questions concerning semantics and linguistics. The word trephine is most certainly a late word as it appeared in the seventeenth century. There are two opposed opinions concerning the person who introduced this new word in cranial surgery. It is broadly accepted that it was Girolamo Fabricius d'Acquapendente (1537–1619) who first presented a new instrument with three legs that was used in trepanations. It was a drilling instrument that he named *'trypana'*. This instrument had three short shanks that run from the centre forming a star. One of the arms ended in a screw tip and it was used to screw it to the skull bone in order to lift it. The other two arms had a more or less enlarged and flattened end and were used to lift the bone fragments by levering them. As the instrument had three tips it was called in Latin *'tres fines'* ('three tips') [6]. It has been accepted that the word 'trephine' comes from the adulteration of the term *'tres fines'* into *'trafina'* in Italian and subsequently *'trefina'*. The Spanish medical etymological dictionary of the University of Salamanca states under the entry *'trefina'* (trephine) that *'no se han encontrado formantes en español. Viene del latín 'tres fines' ('tres puntas') 'de un instrumento para trepanar inventado en el s.XVI por Fabricio de Acquapendente'* (no morphemes have been found in Spanish. It comes from Latin 'tres fines' (three tips), which is an instrument used for trepanning invented by Fabricio de Acquapendente in the sixteenth century). However, this instrument described by d'Acquapendente did not allow making perforations and did not resemble a trephine at all.

Other authors suggest that the origin of the term trephine comes from John Woodall (1570–1643). This author described an instrument that improved the existing trepans in 1639. He called it 'traphine' because it had three edges. This word would ultimately become 'trephine'. The instrument described by Woodall could be used with one hand. It had a T shape, a transverse handle and a mounted shank on one edge with a drilling crown that had a truncated cone shape. He called the instrument *'tribus finibus'* or *'tres fines'*, meaning that it had three tips or edges: two of them forming the transverse handle and the other one in the drilling crown. This instrument, therefore, looks like what we now understand as a T-handle trephine [7]. It is obvious that this tool is not the same one that was described by d'Acquapendente at all. Thomas Wilson Parry

(1866–1945) supports this origin of the word trephine by Woodall, but introducing this very singular comment: *'Trephining: Latin, Tres, three and fines, ends. A terrible word concocted by Woodall (died 1643) when he gave the 'trepan' a handle and evidently decided that the new word must bear some resemblance to the old one, though the one was Greek and the other Latin'* [8].

The terms *'trepanning'* and *'trephining'* were mistaken and used interchangeably in English medical and historical literature. The latter term has a greater acceptance in English language and ended up becoming the word that means any osseous perforation, particularly the cranial ones. The translation of older texts written in other languages into English in the nineteenth century (particularly old medical texts written in Latin) was the reason why the term trephine was introduced and associated with such a broad meaning. Careless readers might think that the word trephine was used in the old original texts. An evidence of this confusion is shown in Benjamin Bell's (1749–1806) book, titled *'A System of Surgery'* where he specifically points out that the only difference between the *'trepan'* and the *'trephine'* was the handle, as *'It (the trepan) differs from the trephine only in the handle being worked like a carpenter's wimble'* [9].

The terminological confusion between trepan and trephine has been present along centuries and persists nowadays. In a paper reviewing the history of trepanation in Africa published in 1994, American neurosurgeons Rawlings and Rossitch transcribe the semiology of the term's 'trepanation' and 'trephination' in this following confusing way: *'Trepanation, or trephination, is one of the most fascinating and ancient practices in the history of medicine. The word trepanation is from the Greek trypanon meaning a borer whereas trephination is a French variant. Trepanation describes scraping, whereas trephination connotes drilling of the skull. For all intents and purposes, they are interchangeable and imply a depression or perforation in the calvarium'* [10].

A similar problem often happens in French medical and historical literature with the terms *'trépan'* and *'trephine'*. The term *'trépan'* keeps its general meaning of cranial perforation in French literature. Therefore, trepanation was generally called *'L'operation du trépan'* in French medical literature of Modern Ages until the end of the nineteenth century. The French authors also often used the words *'trépan'* and *'trephine'* interchangeably, although the difference between both instruments was related to the handle rather than the bone-cutting element. Hence, French authors normally prefer the term *'trépan'* when referring to the driller with brace handle and *'trephine'* for the T-handle driller, which corresponds to the English ones (*'trépan anglais')*. We now include a fragment of the book *'Traité complet de l'anatomie de l'homme'*, which was written by Jean Marc Bourgery (1797–1849). It perfectly shows this issue. An illustration shows two trepanation instruments [11]. One of them has a brace handle and the other a T-shaped handle. Both have the same cylindrical cutting crown mounted on one edge. He calls the first instrument a *'trépan'*, but when he describes the drawing that represents the perforation instrument with a T-shaped handle he calls it *'Tréphine (ou trépan anglais)'*. He states that 'this instrument is nothing but a trepan than can be held with one hand by its transverse handle. Apart from this, the accessory parts of the main instrument are the same'. Other French authors expressly refer to the instruments in the same way. They assimilate the name *'trépan'* for the brace-like driller and *'trephine'* for the T-handle driller, regardless of the drilling instrument that was coupled (normally a trephine crown in both cases of that time).

We are going to use the term trephine in this book when referring to the drilling instrument and the technique that makes a circular cranial opening with a hollow instrument that has a saw on its edge (trephine). It allows obtaining a disc of bone, regardless of the type of handle (brace-like or T-shaped handle). In the following pages will try to describe the devices, detailing in each case the handling and the perforating parts of the instruments.

2.3 Craniotomy

Ancient surgeon only occasionally enlarged the cranial opening obtained after making the initial trepan or trephine in that time. However, as the modern concept of craniotomy did not exist we are going to refer to these large cranial windows generally as trepanations.

The term 'craniotomy' is used in this book meaning a surgical intervention that involves making a cranial opening or window of a large size and with a variable shape. This is achieved by making one or several burr holes and a linear cut on the bone existing between them. It aims usually to carry out a therapeutic surgical intervention in the intracranial space. The first modern craniotomy accomplishing all of these requirements was described by Wilhelm Wagner (1848–1900) in 1889 [12].

The term *'craniotomy'* is defined by the Oxford Dictionary as follows: *'Noun. Surgical opening into the skull'*. The Oxford Dictionary also includes the meaning of the ancient technique that involved breaking the foetus' skull in the birth canal so that it could easily come out (*'Surgical perforation of the skull of a dead foetus to ease delivery'*).

The lexical components of the term craniotomy are *'kranion'* (skull, head) and *'tome'* (cut). The term *'craneotomía'* is not defined in the dictionary of the Real Academia de la Lengua Española (Royal Academy for Spanish Language). The medical etymological dictionary of the University of Salamanca states that the term *'craneotomía'* has a modern origin and comes from the English (*'Craneotomía' (Cirugía) Apertura quirúrgica del cráneo. Leng. Base: gr. Neol. S. XX. Docum. En 1929 en ingl.)* ('Craneotomy' (Surgery). Surgical opening of the skull. Original language: Greek. Neologism. Twentieth century. First documented in 1929 in English language). This etymological consideration is not correct as the terms *'craneotomie'* and *'craniectomie'* were used decades before in medical texts by many French authors. At the end of the nineteenth century, in year 1893 [13], the French author Lèon Gallez (1864–1898) mentioned the craniectomy and the trepanation technique as well as the increasing use of the former term in his work *'La trépanation du crâne'*, where he wrote: *'J'estime qu'il est préférable de la dénommer craniectomie, terme ne désignant que l'acte opératoire lui-même, abstraction faite des instruments à utiliser pour son exécution. On observe, en effet, l'heure actuelle, la tendance qu'ont les chirurgiens à substituer cette nouvelle appellation à l'ancienne'* (I think that it is better to call it craniectomy, a term which designates only the operative act itself, apart from the instruments to be used for its execution. At present, we observe the tendency of surgeons to replace this new name with the old one). Accordingly, George Marion (1869–1960) established in 1905 in his book *'Chirurgie du Système Nerveux'* that the cranial opening can be carried out *'Par relèvement d'un lambeau osseux circonscrit de façon variée; l'opération prend alors le nom de craniectomie à lambeau, on devrait dire plus exactement craniotomie'* (By raising a bone flap circumscribed in a variety of ways; the operation then takes the name of flap craniectomy, we should say more exactly craniotomy) [14]. Many other French and English authors used both terms 'craniotomy' and 'craniectomy' interchangeably in that time.

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Part II

Magic Times. Trepanation in Primitive Cultures

Deseo insistir que con estas trepanaciones no se podría solucionar hoy en día ningún proceso patológico endocraneal, con la excepción, un tanto discutible, de un hematoma o absceso

Domènec Campillo (1977–)

3 Facts and Myths of Primitive Trepanations

3.1 Trepanations and Primitive Cultures

We can state that trepanations are the oldest surgical interventions we have evidence of [1, 2]. It is also possible to point out that almost all human cultures, in almost all geographical locations and along the time line, have carried out any type of cranial opening with very different purposes, no matter whether they were known or unknown. In this chapter we are going to focus on cranial openings or trepanations carried out within primitive cultures, including cultures worldwide and in different chronological periods, particularly those performed during the European Neolithic 5000 to 3000 years BC, the American pre-Columbian times until the Spanish Colonisation during the sixteenth century and by some Oceanic or African tribal cultures during the nineteenth and twentieth centuries.

We are going to consider as primitive cultures those ones that meet the requirements specified below. First, they lack any written document; that is, they are prehistoric. It is noteworthy that, for example, the Inca civilisation, which was very developed, did not have any known writing system, although the '*quipus*', which were some sort of macramé made of cords with knots, were supposed to have such paper. Actually, some primitive cultures do have writing remains, such as the Aztec, the Maya or other Mesoamerican writings. However, they cannot be read as they have just started to be decoded. The lack of writing remains is the reason why almost all what is known from these cultures concerning trepanations comes from the study of human bones and some marginal archaeological remains that let us contextualise the findings. Another feature is that these civilisations carried out certain rites with their corpses. To preserve the cranial remains it is necessary to bury the corpses. This is the only technique that allows to preserve the trepanned osseous remains over time so that they can be studied. Other types of mortuary rituals, such as cremation, make it impossible to preserve the bones. In those cases when there are no written documents, it is unfeasible to determine whether trepanations were carried out or not. Another characteristic element of primitive cultures regarding trepanation techniques is that they used solutions and instruments that were suitable for each type of drill and in keeping with the materials and technologies of their geographical and historical situation. In general, primitive cultures are also characterised by settling in restricted geographical locations with few or very limited trading/cultural activities with the nearby peoples or those ones living in the same period. This is why we cannot obtain information from them in an indirect way. As a consequence, an essential, final, and common feature of primitive cultures is that many aspects of trepanation are unknown or are based on speculations or theories. Hence, we must affirm that actually it is not known why the

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trepanations were carried out or the purpose thereof. In this regard, the only link between these primitive trepanations is that they were some sort of very primitive medicine of a magical or religious nature with some undeniable empiric elements.

According to these criteria, primitive cultures can be either extinct or contemporary. As for the latter, they show all the general features that have been pointed out. Fortunately, we have, in some cases, direct testimonies of the trepanations provided by reliable independent witnesses. They are even documented by means of photographs or films.

It is now important to understand, narrow and adequately use the term 'trepanation'. From a strict semantic and etymological point of view, we have defined the trepanation as a surgical osseous drill. Trepanation refers to drilling any bone of the anatomy. Cranial trepanation specifically refers to trepanning the skull and particularly the cranial vault, with no connotation regarding the size of the cranial opening or the techniques used to carry it out.

The modern definition of the term 'trepanation' also means that the drilling must be surgical; that is, it must have a diagnostic or therapeutic purpose. However, in the cranial openings carried out by primitive cultures we cannot accurately prove that there was a diagnostic or therapeutic aim beyond the magical, religious or empiric objective. For this reason, when we use the term 'trepanation' in this book within the context of primitive cultures, we will completely remove from it any possible association with any kind of medical or surgical intervention. For this same reason, we will not use the term 'surgeon' when referring to the person who carries out the trepanations within primitive cultures, let alone the term 'neurosurgeon' when referring to the person in charge of cranial trepanations.

We will subsequently review the trepanations carried out in these primitive cultures. We will highlight the technical and technological aspects of such practices, without forgetting the cultural context in which they were performed. Trepanations in primitive cultures are also known as 'prehistoric trepanations' or 'ancient trepanations' in other works or studies.

3.2 History of 'Prehistoric Trepanations'

It is nowadays accepted that the scientific interest on trepanations of primitive peoples arose from Ephraim George Squier (1821–1888) and his convenient relationship with Paul Broca (1824–1880) [2–5]. Squier was an American diplomat and archaeologist who, after completing a commission from the American Government in Peru, spent the remaining available time focusing on his passion for anthropology and travelling around the country. During his trips he got a skull on which he observed and described the evident signs of a frontal cranial trepanation. Such skulls had been found in the area of Cusco (Peru) and belonged to the pre-Columbian period. Afterwards, it was dated from the years 1400 to 1530.

Squier described how he got the skull, actually a gift of the Señora Zentino in his book *'Peru. Incidents of travel and exploration in the land of the Incas'*, published in 1877 (Squier [6]). Squier writes: 'In some respects, the most important relic in Senora Zentino's collection is the frontal bone of a skull, from the Inca cemetery in the valley of Yucay, which exhibits a clear case of trepanning before death. The senora was kind enough to give it to me for investigation, and it has been submitted to the criticism of the best surgeons of the United States and Europe, knowledge of surgery among the aborigines yet discovered on this continent; for trepanning is one of the most difficult of surgical processes. The cutting through the bone was not performed with a saw, but evidently with a burin, or tool like that used by engravers on wood and metal. The opening is fifty-eight hundredths of an inch wide and seventy hundredths long' (Fig. 3.1).

After coming back in 1865 he presented the skull to the New York Academy of Medicine so that it could be studied. On its final report, the Academy showed their complete scepticism about the fact that the trepanation had been carried out before dying. Squier, who was disappointed after the report, sent the skull to Paris so that it could be studied by Broca, who was considered by then a worldwide reference in terms of

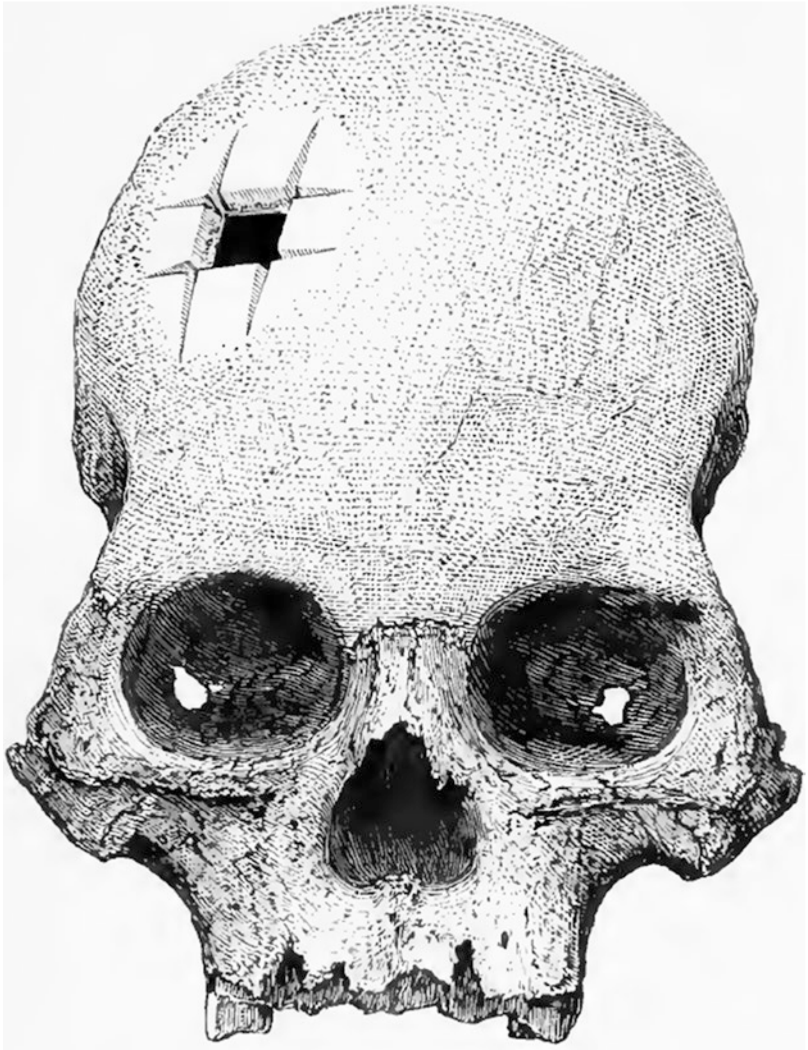

Fig. 3.1 Skull brought by E. George Squier from Peru (Squier EG. Peru. Incidents of travel and exploration in the land of the Incas. New York: Harper & Brothers: 1877)

the brain and its pathology. He also had founded the Society of Anthropology in 1859. Broca concluded on his report that not only had this person been trepanned alive but also that he/she had survived the trepanation.

The report of the study of the skull by the Society of Anthropology of Paris was published on the *Bulletin de la Société d'Anthropologie de Paris* on the 4th of July of 1867 as a *'Cas singulier de trépanation chez les Incas'* [3]. No images of the skull were included in the publication. In this report, Broca immediately acknowledges that Squier, *'le première archéologue de l'Amérique'*, was the scholar who discovered the skull, entrusted him with it and gave him all necessary guarantees about its origins and authenticity. This is followed by a detailed description of the skull. He points out that there is a whitish elliptical depression on the frontal region with a size of 42 × 47 mm. The surface of that denuded area shows porosities on its outer table which, from his point of view, make it impossible for the individual to have survived less than 7–8 days after the denudation. M. Nélaton, who also studied the skull, thinks that the person might have survived 15 days. After that, the trepanation is described. It was carried out within a depressed area with four linear incisions that made up a square of 15 × 17 mm. Broca highlights the shape and the methodology of the trepanation, which was completely different to the Indo-European trepanned skulls. He analyses the instruments used and adds Squier and other researcher's ideas. He finally discusses the indications and the boldness of the trepanner as there were no fractures and states that *'trépaner sur une fracture apparente au fond d'une plaie, c'est une conception assez simple, et qui n'implique pas l'existence d'un art chirurgical bien avancé; mais ici la trépanation a été pratiquée sur un point où il n'y avait pas de fracture, où même très-probablement il n'y avait pas de plaie, de sorte que l'acte chirurgical a dû être précédé d'un diagnostic. Que ce diagnostic ait été exact, comme cela est probable, ou qu'il ait été faux, nous sommes toujours autorisés à en conclure qu'il y avait au Pérou, avant l'époque européenne, une chirurgie déjà assez avancée'* (To trepan on an apparent fracture in the bottom of a wound is a fairly simple conception, and does not imply the existence of a well-advanced surgical art; but here the trepanation was performed on a point where there was no fracture, where even very probably there was no wound, so that the surgical procedure had to be preceded by a diagnosis. Whether this diagnosis was correct, as it is probable, or false, we are still authorised to conclude that there was in Peru, before the European epoch, a surgery already advanced enough).

The study of this skull awoke in Broca not only admiration for the case but also a personal interest in reviewing a set of old skulls that he and other researchers had found in France. To do so, he counted on the help of P. Barthélemy Prunières (1828–1893), one of his collaborators. Prunières himself had discovered a drilled skull, which he initially considered a ceremonial vase, beside a dolmen in 1865. In addition, other similar findings in France were documented. They have been classified as accidental or postmortem holes. In 1839 Morton included drawings of trepanned skulls in a book. However, he considered that the cranial opening was due to a trauma. Other researchers of that time found far older references of drilled skulls discovered in Europe, for example a finding dated in Cocherel (Ille de France, France) in 1685 and another one in Nogent-les-Vierges (Oise, France) in 1816. Both openings were also considered to be due to a trauma. Hence, Broca and Prunières, after studying Squier's Peruvian skull, systematically reviewed the skulls with drills that were attributed to traumas and ritual or ceremony practices. Many of them were considered trepanned skulls from that moment on. In addition, these authors laid the foundation for a body of doctrine on a topic that was called by then 'Prehistoric Trepanations'.

This paradigm shift in the type of opening of those skulls was not immediate. It was necessary to overcome an initial phase of scepticism as it was considered almost impossible that primitive cultures could successfully carry out surgical interventions that, in the medicine of the second half of the nineteenth century, were performed on an exceptional basis and with far from encouraging results. What is worse, these interventions were more limited in terms of extension of the cranial opening, areas approached and, in general, less sophistication concerning any technical aspect. Something similar happened with the Palaeolithic paintings of the Altamira Caves in Spain, which were discovered in 1880. European specialists considered them a fraud for more than 20 years as they thought they showed too much artistic quality to have been painted by Palaeolithic peoples.

However, thanks to Broca, researchers continued reviewing the European Neolithic drilled skulls. This allowed that in the end many of them were considered trepanned and new specimens were provided soon. A new phase of admiration for the quality of the findings started then. Hence, in 1894 the French anthropologist Jean-François-Albert du Pouget (1818–1904), Marquess of Nadaillac, considered a cranial trepanation that had been found near Dieppe (France) as 'a surgical intervention that had been carried out so skilfully as if one of the most renowned surgeons had performed it' [7].

Once they recovered from this shock, all of these researchers set out the fundamental questions concerning the techniques, survival and purposes of trepanation and started a true and valuable scientific study.

3.3 Indications for Trepanation in Primitive Cultures

The most insolvable issue is/are the reason(s) why primitive cultures carried out a trepanation. In this regard, there are different points of view. However, they are all speculative and are based in contextualising the supposed indication for the trepanation within the cultural elements that were known or attributed to the specific civilisation that carries it out. As there are no written evidences, the main reasons proposed are based on ritual (particularly religious, magical or initiation rites), medical (headache, psychiatric disorders, epilepsy) and surgical purposes (treatment of wounds, fractures or cranial or intracranial lesions) (Fig. 3.2).

A standpoint with many supporters admits that primitive trepanations were exclusively carried out due to surgical or medical purposes. An argument in favour of this opinion is that some of the cases of trepanned skulls show some pathology, such as skull fractures [8] or mastoiditis [9]. These findings evidence reliable, external physical signs that can be proved on the trepanned skull. In the rest of the cases, the trepanation could have been carried out to treat intracranial lesions or diseases without cranial marks. These intracranial disorders, in any case, would not have left any evidence on the osseous remains of the trepanned skull. Another similar argument is that trepanations were carried out to treat neurological diseases, such as epilepsy, headache, psychological or psychiatric disorders or illnesses or symptoms of any other type. As they do not involve any organic lesion, they could not have left any evidence on the skull. The main criticism to this speculative argument is that it would be too risky to assume the existence of enough medical knowledge to make a clinical and topographic neurological diagnosis by the primitive medicine man that was only achieved in modern medicine at the end of the nineteenth century by neurologists. In addition, even if we admitted the previous argument, that is, all trepanned cases showed a pathological condition and the disease was localised, the frequency of trepanations in many cultures exceeds the current one in the Western world, where this intervention is only carried out with a diagnosis of intracranial pathology. Moreover, many trepanations were clearly carried out after the death of the individual.

As it has been pointed out, it is a fact that there might be a relationship between trepanations and cranial or intracranial pathological conditions that can be recognised on the osseous remains. However, this relationship is anecdotal. Nowadays, thanks to the early diagnosis and the use of modern imaging techniques, it is very unusual to make a diagnosis of cranial or intracranial pathology based on the information obtained from their direct or indirect effects on the osseous structure of the skull [10]. However, it is true that many progressed pathological conditions are able to cause great osseous modifications on the skull. These changes allowed making a diagnosis of cranial and intracranial lesions by means of direct and indirect radiological signs in simple skull radiological studies until well into the twentieth century. In fact, these indirect signs of intracranial pathology, which presumably could be easily recognised on trepanned skulls, cannot be found.

However, it is undeniable that some patients were trepanned due to a cranial trauma or infection. In these cases, the trepanner might have had a healing purpose. It seems logical to think that if trepanations were carried out worldwide and over centuries (no matter what their purpose was), it was because the trepanned patient hoped to obtain any benefit. The fact that such benefit was achieved is what allowed to continue with the practice. We might think that if some individuals with trauma or infections got to solve their problems with trepanations, this technique was used more frequently. Chance and observation are basic elements that allow to recognise and continue with a successful practice in an empiric environment. The purely empirical element is a very primitive component of medicine.

However, it is possible that trepanation among primitive peoples was a practice related only to military surgery, used exceptionally outside this area. It is also possible that many fractures treated with trepanation may not be visible because they were eliminated by the trepanation itself. We must bear in mind, as will be detailed below, that for centuries the surgical treatment of cranial fractures was made in Europe following the Hippocratic postulates. In these, the treatment of the cranial fracture consisted of its mere elimination of the fracture line by scratching or the fractured bone with different techniques of skull trepanation.

Many people consider that this hypothesis is too speculative. In this regard, Domènec

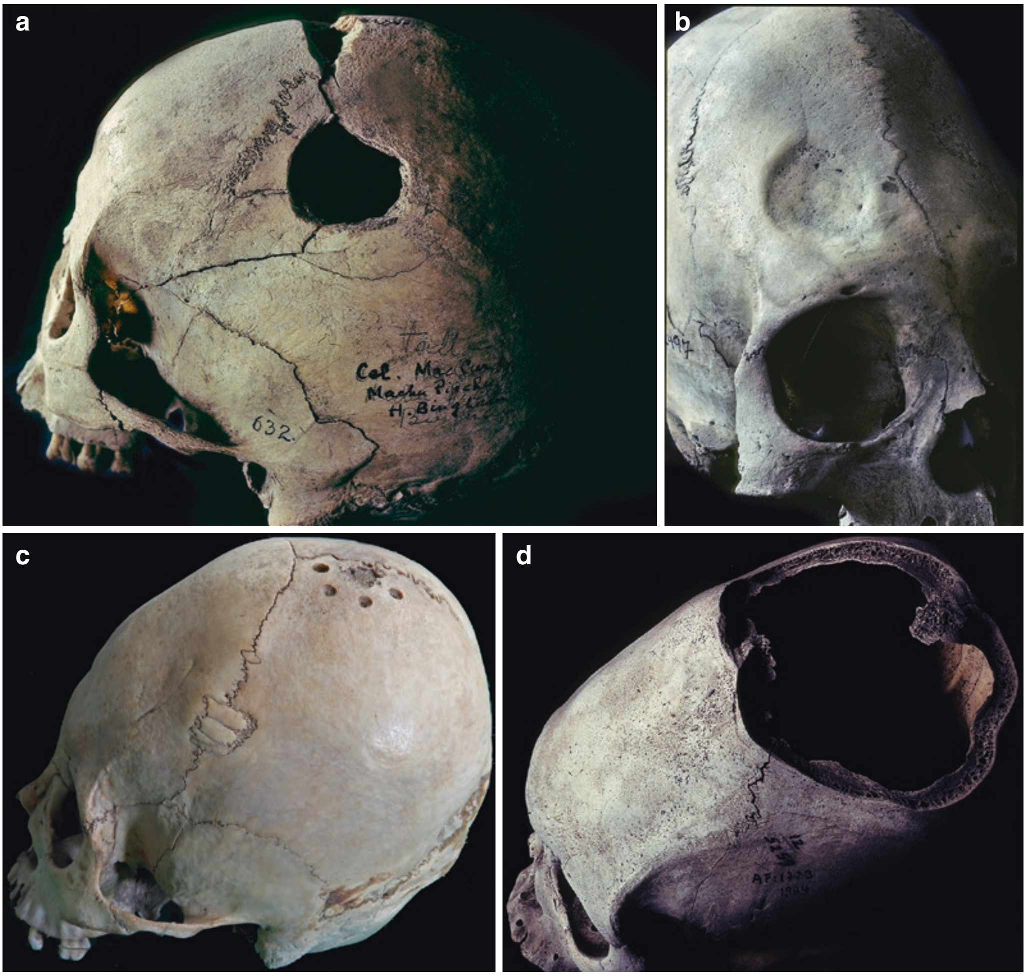

Fig. 3.2 Figure showing some Peruvian trepanned skulls with different alleged purposes. (**a**) Trepanation in a case of a vast skull fracture, with no survival (Inca, Paucarcancha, near Machu Puchu, Peru). (**b**) Trepanation in a case of right frontal lineal fracture, showing a long survival (Hearmey, coastal area, Peru). (**c**) Four holes made in the left parietal bone around an undetermined bone lesion near the sagittal suture in the middle line of the skull. The trepanation was not completed (Huari culture, Peru). (**d**) Massive midline trepanation, with removal of a large part of both parietal bones and the posterior part of the frontal bone. A hypothetical bone lesion might have been removed with the elimination of this large piece of bone. A bone bridge below the sagittal sinus was in the skull when found but it was lost following the restoration works (Paracas, Peru). (**e**) Left frontal sinus trepanation made with several perforations in a traumatic or infectious lesion (Peru). (**f**, **g**) Skull with a double trepanation. The anterior is located in the right frontal bone and is related with a linear skull fracture extending to the orbit and showing no signs of survival. The posterior is located in the right parietal bone and shows signs of a long survival. (**h**) Deformed and trepanned skull (Paracas, Cerro Colorado, Peru). (**i**) Skull showing five trepanations showing signs of healing. The skull shows no fractures neither bone lesions (Calca, Valle Sagrado, Cuzco, Peru) (courtesy of José María Fernández Díaz-Formentí')

Fig. 3.2 (continued)

Campillo (1927–) was convincing when he stated that *'Deseo insistir que con estas trepanaciones no se podría solucionar hoy en día ningún proceso patológico endocraneal, con la excepción, un tanto discutible, de un hematoma o absceso'* (I'd like to insist on the fact that nowadays these trepanations would not solve any endocranial pathological process, excepting a haematoma or an abscess, but this is arguable) [11].

In fact, the truth is that we do not know how primitive peoples faced diseases. Contemporary primitive trepanations include references to trepanations carried out after trauma or infections or due to headache. However, we must highlight that even in those cases trepanation is the treatment itself. It aimed to obtain benefits just by carrying out the technique and not to know or solve the real causes of the patient's problem. The shaman performs a trepanation; they do not treat the fracture or infection or fight the supposed physiopathological mechanism that causes the patient's headache. This is one of the core characteristics of magical medicine.

A circumstantial but demonstrative argument of what is being discussed here is based on the fact that if Inca trepanations had been a routine medical-surgical practice within the context of a highly sophisticated medicine, the Spaniards would have shown some interest in it. However, there are no references about this practice. Juan Pizarro (1500–1536) was the brother of Francisco Pizarro, conqueror of the Peruvian Inca Empire. Juan Pizarro died in the battle of Sacsayhuamán, an Inca fortress near Cuzco. He was hit in the head by a large stone thrown by an Inca warrior as he tried to climb the high walls of Sacsayhuamán. Although the Spanish army counted on multitude of native allies, it was not trepanned neither by the Spanish surgeons nor by the local shamans. Other observations support this fact. The Spanish soldier and poet Garcilaso de la Vega (1501–1536) describes the case of a Spanish soldier with a severe head injury who died without any kind of cranial surgery: '*Uno de los muertos fue el capitán Pedro de Fuentes, que fue teniente de Gonzalo Pizarro en Arequepa (*sic*); dióle otro caballero con una porra, de la que los indios tenían en su milicia, a dos manos de un golpe encima de la celada, tan bravo, que el pobre Pedro de Fuentes resurtió de la silla más de media vara de medir en alto y cayó muerto en el suelo con la cabeza hecha pedazos dentro en la celada, que el golpe se la abolló toda'* (One of the dead was Captain Pedro de Fuentes, who was Lieutenant of Gonzalo Pizarro in Arequepa (sic); he gave him another knight with a truncheon, of which the Indians had in their militia, two hands above the blow, so brave, that poor Pedro de Fuentes rose from the chair more than half a yardstick high and fell dead on the floor with his head smashed inside in the trap, that the blow was dented all) [12]. An unlikely hypothesis would be that, by chance, the trepanations had suddenly vanished from the culture of the Inca peoples shortly before the arrival of the Spanish conquerors.

Once the general medical-surgical indications for trepanation have been dismissed, we can postulate sociocultural reasons. The social or cultural differences between primitive civilisations can be extreme. Hence, the sociocultural environment of the European Neolithic is clearly different to the Inca Empire, which was more complex and developed. This is why it is hard to think that the same solution for the same problem was proposed in both cultural atmospheres using the same arguments. The *'kisii'* trepanations can be considered acculturated primitive trepanations with the incorporation of contemporary technology in terms of modern surgical instruments. However, they maintain all the traditional elements of primitive trepanations concerning their indications, procedures and people involved in their practice. The analysis of the circumstances of the trepanations carried out in the North of Africa until very recently is more problematic as technological contamination barely exists there. However, there are references to a practice of many centuries within a family of trepanners and the existence (although this has not been documented) of handwritten texts containing the trepanning instructions and techniques. In case this was true, it would not be risky to assume the possibility that this tradition had its origins in the Arabic medieval medicine, which as mentioned later is based on the Hippocratic texts that are the pillars of modern scientific medicine.

Contrary to those considerations, there are global and more pragmatic proposals, like those made by Domènec Campillo (1927–), one of the Spanish opinion leaders on palaeopathology. He postulates that all trepanations would have a magical purpose. Magic is the way primitive cultures anticipate and solve their problems, regardless of their nature. Magic works by means of rites that the shaman or medicine man of the tribe carries out. One of those rites is the trepanation but we cannot conclude anything else about the real justification of its practice on a specific case. This would explain the poor relationship between trepanations and pathology, how variable this practice was, the high frequency of trepanations in some cultures and the surprisingly high survival rate of trepanned individuals [11].

The elements of magical medicine were well defined by Pedro Laín-Entralgo (1908–2001). This Spanish expert in the history of medicine considered that magical medicine was based on the idea that people firmly believed in the effect of entities and invisible forces that were more powerful than men. These forces could be controlled to some extent by men themselves through rites or ceremonies. The effectiveness of these actions is based on several factors: the solemnity of the rite itself (which must always be carried out the same way), the power of the person who holds the rite (in the case of healing rites, the witch doctor, wizard, curer, shaman or medicine man), the place or the environmental circumstances where the rite is held and finally the social status of the patient [13]. All these elements can be recognised in trepanations carried out by primitive cultures.

It is surprising that the magical-religious component of primitive trepanations has been temporarily resurrected in developed civilisations. This is, for example, the case of 'The Extraction of the Stone of Madness'. This activity was artistically expressed in the spectacular works of the Flemish painters from the sixteenth century. Another example that is more contemporary can be found on the Internet when searching for the results of 'trepanation'. It is possible to find certain groups who support the therapeutic ritual trepanation proposed by the Dutch author Hugo Bart Huges (1934–2004) and that allowed to balance blood and cerebrospinal fluid flows, pressures and volumes that are altered in the human species due to the standing position. This current has led to exceptional cases of voluntary trepanations and even to self-trepanations [14].

In modern primitive cultures from the North of Africa and the Caucasus, witnesses often record and document the implications of complaints of trepanned individuals. These were based on the tribe's practices and customs and belong to the common law of such cultures. An extreme example of indication for trepanation is its use as a legal evidence to determine the injury suffered and the corresponding compensation for the injured person. Adolf Dirr mentioned in 1928 the events recounted by F.I. Leontovich on a work published in Odessa in 1883 and where he related the customs of the *'ingush'* tribe from the Caucasus. That tribe had an injury compensation system based on the severity thereof. Concerning head injuries, a simple wound on the pericranium that did not expose the bone was compensated with a sheep and certain quantity of brandy, as well as all the costs derived from the treatment. The compensations increased until reaching a maximum, which corresponded to a brain injury. The court only established the compensation once the injuries had healed. This could happen several months later and allowed the patient to include new complaints and aches then. In the event of a conflict, it was solved by means of the trepanation. The medicine man made a cross-shaped cut on the area of the trauma or the pain. They analysed the injuries the patient suffered from to determine the compensation and eventually solve them. If the patient died as the result of this judicial trepanation, the trepanner was blameless and the attacker could be accused of the death of the patient [15].

3.4 Current Panorama of Trepanations in Primitive Cultures

As a consequence of all that has been described it is possible to identify a set of common patterns based on solid evidences in the trepanations carried out by primitive cultures. There is also a great deal of unclear questions which have a very speculative interpretation. This might be the reason why primitive trepanations are still surrounded by a mysterious atmosphere.

Since they were discovered, the trepanations carried out in primitive cultures have always been accompanied by occultism, esotericism and discretion. This can be explained due to the difficulties to be globally understood and the impenetrability concerning its comprehension showed by some part of the first scholars at the end of the nineteenth century. These same elements multiply and increase when studying the trepanations in social media from a pseudoscientific point of view, which leads to nonsense scenarios. The basic error in this point of view is due to considering that trepanation in primitive cultures belongs to the same category as current craniotomy, which is a rational and scientific medical intervention. As we have mentioned, trepanations in primitive cultures are nothing but a magical-religious activity with some marginal elements that might be included within empirical medicine.

For this reason, it is important to completely separate these types of trepanations from the craniotomies that are carried out within the field of modern neurosurgery. This rotten relationship is often established repeatedly in the media, as well as in pseudoscientific environments and in scientific atmospheres and publications. It is surprising that this conceptual misuse is allowed and fostered by prestigious neurosurgical journals. Hence, *Neurosurgery*, the most important journal in neurosurgery and with the highest scientific impact, published in 2000 a paper entitled *'Preconquest Peruvian neurosurgeons …'* [16]. In the prestigious journal *World Neurosurgery*, it was even stated that *'the neurosurgical profession must be one of the most ancient jobs in the world'* [17]. Finally, the *'Youmans Neurological Surgery'*, the currently most respected treatise on neurosurgery reoffends by establishing that *'Neurosurgery is in many ways one of the most ancient of professions'* [18]. Even the anthropologists insist on the same mistake in prestigious palaeopathology journals. Hence, Moghaddam and collaborators literally said on the *International Journal of Paleopathology* in 2015 that *'the high survival rate indicates that neurosurgeries were often performed successfully in prehistoric times'* and that *'Neurosurgery appears to be one of the world's oldest specialised professions'* [19].

The Neolithic, Peruvian or *'kisii'* primitive trepanner cannot be considered surgeons, let alone neurosurgeons. This is basically because neurosurgery is a surgical specialty that was established in the 20s or the 30s of the last century. The surgeons who carried out the surgical trepanations over centuries since Hippocrates cannot be called neurosurgeons either. It is curious that nobody has done so with Hippocrates, Galen, Andrés Alcázar, Ambroise Paré or Doyen. We are going to prove in the next chapters that primitive trepanations have nothing to do with modern neurosurgery craniotomies or with the trepanations carried out before modern neurosurgery. The most important difference is that in the latter the trepanner (surgeon or neurosurgeon) has a clearly therapeutic purpose based on anatomic and physio-pathological knowledge, regardless of the scientific paradigms on which their intervention was based at the moment when it was done. This means that the cranial opening is a clinical intervention that belongs to scientific medicine.

3.5 Myths About Primitive Trepanations

However, we must admit how easy it is for an observer or a scholar who is not an expert on modern neurosurgical technique to make the mistake of giving importance to esoteric elements related to primitive trepanations and considering easily explainable facts as real myths. We are going to describe some of those myths and show the arguments that distort them.

The first myth is the serious consequences for the patient of an eventual brain injury (no matter how small it is) that could be iatrogenically caused during the trepanation. If this fact is considered acceptable it is obvious that primitive trepanner had a deep knowledge to dare to carry out the trepanation. Non-experts are incredibly worried about the quality of the organ beneath the skull, the brain, the deleterious consequences of its handling and the daring to face this problem without a solid neuroanatomical, neurophysiological and neurosurgical knowledge. Some people consider that all or some part of these aspects had to be known and controlled by primitive peoples if they dared to trepan. A classical concern is that accidental or intentional handling of the brain cortex, even if it is absolutely accurate, during the trepanation could cause serious neurological effects and severe functional consequences to the trepanned individual. Nowadays it is accepted that actually there are no cortical or subcortical areas of the brain without any function. In fact, any cortical or subcortical area of the brain is potentially eloquent. However, eloquence is not function. Eloquent brain areas are defined as specific cortical or subcortical brain regions that can be easily excited and that produce a foreseeable and repetitive response that can be easily detected. However, among all eloquent areas only some of them are related with functions relevant for the patient, particularly those ones related to mobility, speech, memory or vision. Hence, it can be possible that injuries with a size of just a few millimetres in motor and speech eloquent areas can have a functional significance for the patient and translate into severe neurological deficits. However, injuries with a size of several centimetres in other large areas of the brain cortex can be tolerated by the person without causing severe neurological or functional deficits, have a very limited impact or can be almost undetectable without sophisticated studies. An additional argument of the ignorance of the anatomy on the part of the primitive trepanner is that they were almost randomly done all over the surface of the skull and made trepanations in cranial locations with high vital risk for the patient, as the openings done on the dural venous sinuses. These regions were forbidden for scientific trepanation until the eighteenth century, along with others of less relevance such as cranial sutures, frontal sinuses or areas covered by muscles. Moreover, we do not know if primitive trepanner opened dura mater because the skull's remains cannot tell us nothing about this particular point. Again, the opening of the dura mater was not a routine until the end of the nineteenth century.

A second myth that concerns non-experts is the expectable difficulty to open the skull due to the firm belief in its high mechanical resistance. Indeed, the central nervous system of vertebrates is entirely well protected by bone. This is due to the fact that it is formed in very early stages of the embryonic development. A neural crest is formed from the ectoderm on the dorsal side of the embryo. It is later invaginated to form a neural tube which is isolated within the mesodermal tissue. It will be located dorsally and very close to the notochord, the main element that induces the embryonic development in these early stages. The spinal cord, the simplest element of the central nervous system, is metamerically protected by the vertebrae in all of its extension. Vertebrae are bone structures with enchondral ossification. They are massive and very powerful as they allow the insertion of the strong retro-somatic and presomatic muscles. The organisation is more complex in the cranium as the segmental organisation disappears and the structure that is equivalent to the vertebrae forms a solid and complex osseous structure, the base of the skull, which protects the sense organs and the deepest and most atavistic parts of the encephalon. However, the volume of the brain hemispheres is particularly large in vertebrate animals. In humans, the brain cortex has a large surface area, regardless of its great volume. This is possible as it folds and forms numerous sulci, fissures and gyri. Moreover, this volumetric growth of the human encephalon dramatically increases during the final stages of the embryonic development and maintains a slower pace after birth. This is why the osseous protection of the brain cortex (the cranial vault) requires a fast and malleable process of bone formation and surface growth, which is achieved by a membranous ossification mechanism. Indeed, the cranial vault is formed by coaptation of several osseous plates, which grow on their surface, whereas the encephalon has a volumetric growth. They end up forming the cranial vault, a pretty simple osseous structure concerning its anatomical organisation.

An adult's skull has a thickness of around 6–7 mm and is made of two layers of thin compact bone (the internal or vitreous table and the outer table) and a layer of cancellous bone or diploe in between. The cranial vault can resist direct tangential impacts as it is a bit elastic and deformable. In addition, the trauma dissipates part of its mechanical energy by displacing or breaking pericranial soft tissues. The cranial bone has a lower resistance against direct perpendicular impacts as mechanical overloads are produced during compression and distraction on the outer and internal tables. When these overloads are high enough, they lead to a mechanical failure and the fracture of one or both tables. However, the skull can be easily drilled by a rotation or friction mechanism. This is particularly evident on the dried skull, without pericranial soft tissues or even if the person does not defend himself or herself as they are dead, unconscious, immobilised or collaborated during the procedure. The fact that many cultures have drilled the skull using different technologies shows how easy this procedure can be.

A third myth that astonishes non-experts when analysing trepanations carried out within primitive cultures is the false belief that trepanation was a sophisticated surgical intervention, as it is believed that it had to be carried out in similar conditions to the current practice. This admiration is the reason why it is often stated that trepanation is the most ancient surgical intervention we know about or that neurosurgeons were the first surgeons in the history of medicine. First, trepanation was usually carried out without any structural brain pathology. There are trepanned skulls which evidence the existence of a traumatic or infectious cranial pathology, but this is an exceptional event. Only in a few of those cases would it be possible to assume a healing purpose by the trepanner. As we have shown, there is not enough information that lets us affirm that primitive trepanations had a therapeutic aim or that they were able to solve intracranial pathologies, which, in addition, had to be diagnosed and localised previously. Trepanations do not require any sophisticated instrument to be carried out. Diverse experimental studies have repeatedly proved that a human skull can be rapidly trepanned with an abrasive or a cutting stone, animal teeth or a hard-wooden shank. Concerning this idea of making the trepanation in primitive cultures look like current neurosurgery, several publications have tried to find the solutions applied by primitive cultures to face other basic problems that are related to surgery, such as anaesthesia, analgesia, haemostasis and antisepsis. As a consequence, they end up making theories and fantasising about the use of hallucinogens, narcotics or alcohol as analgesics and/or anaesthetics, tourniquets or compressive bandages and cauterisation as haemostatic mechanisms or even the use of certain antiseptic remedies based on herbs and minerals. What is actually done is naively transferring the current solutions for these problems to another time and place.

Proving that these beliefs or myths are false does not mean that we cannot admit the global complexity of the procedure, which certainly required adequately trained people who specifically carried out this task and had the required instruments. A cranial trepanation cannot be improvised. Once we have accepted this idea, we can imagine that trepanation was quite an event in social groups where probably one of the most sophisticated technical interventions we know about was carried out. However, in this respect, the trepanation has the advantage of leaving an indelible mark on the osseous remains of the trepanned individual, which can be preserved under certain taphonomic circumstances. The persistence of the osseous mark of the trepanation on the skull that has been found some time later is what lets us know that the trepanation was indeed carried out. On the contrary, other hypothetical very complex surgical interventions carried out on, for example, soft tissues, viscera or vessels could only be preserved and recognised if the corpse had been mummified in a ritual or natural way, which is less frequent. Likewise, a possible intervention on the brain of a trepanned individual cannot be proved as the brain cannot be preserved.

3.6 Remarks and Comments

The trepanation that was practised in primitive cultures has been carried out worldwide and throughout history [20]. Due to the lack of written evidence and the shortage of remains, most of the conclusions concerning the purposes, techniques, technology and results are speculative. The information known forces us to classify these practices within magical medicine. Some trepanned skulls, particularly those from the pre-Columbian period, are specially interesting due to the size of the cranial opening and the strictly aesthetic result. However, this does not mean that they had a great knowledge beyond the technical empiricism. Primitive trepanations aimed to obtain a benefit just by the mere and stereotyped fact of carrying them out, regardless of the existence of an underlying pathology in the trepanned cranial remain in most cases. This pathology could be evident (normally due to a trauma or an infection) or presumable (supposedly due to traumas, headache or neurological symptoms that do not leave any mark on the trepanned cranial remain). The trepanning techniques and instruments were of the most varied kinds, as drilling the skull is rather easy. The differences between the cultures depend on the availability of the materials and their technological development. The trepanations were carried out by medicine men who had been trained and were specifically in charge of this task. It was a job that probably had a strong family tradition. The trepanations only affected the cranium and the pericranium. Although there are no palaeontological data that support or reject this idea, there are no written evidences from witnesses of contemporary primitive trepanations that suggest that the dura mater was opened. The preservation of the dural barrier, the lack of intracranial pathology and the good general condition of the trepanned individuals might explain the high survival rate that is evidenced by the osseous signs of bone remodelling. Many trepanations were clearly carried out post-mortem and many others have no osseous signs of survival. This is why it is not possible to know whether the patients were alive or not when the interventions were carried out. Some trepanations were incomplete. Finally, some intentional handling techniques of the skull on alive individuals had no trepanning purposes. When finding a skull with a cranial window, a series of scientific studies (that are increasingly sophisticated) are first performed to prove that it was not a pseudotrepanation.

The trepanations of the primitive cultures are already over. The spread of modern Western civilisation and uses in all corners of the world makes it virtually impossible for it to continue its practice in any contemporary culture. Leaving aside certain technical aspects, most of the questions related to primitive trepanation are conjectures or the result of the transcultural application of the scarce safe data available.

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4 Techniques and Tools for Primitive Trepanations

4.1 Techniques for Trepanation in Primitive Cultures

Some of the first issues addressed by the anthropologists of the nineteenth century were the technical aspects and the technology used in primitive trepanations. Since the discovery of pre-Columbian trepanations and the rediscovery of the European Neolithic trepanned skulls there have been many experimental studies aimed at establishing the instruments and the techniques needed for such practice. This is due to the lack of archaeological or written remains that let us determine the use of specific instruments for this purpose. There is no written information about the procedure either.

Just Lucas-Championnière (1843–1913) includes in his book called *'Les origines de la trépanation décompressive. Trépanation néolithique, trépanation pré-colombienne, trépanation des Kabyles, trépanation traditionnelle'*, which was published in 1912, many examples of experimental trepanations carried out by himself and other researchers at the end of the nineteenth century and the beginning of the twentieth century [1]. Among the experimental essays of cranial drilling, he describes and replicates the cranial opening by scrapping with Müller's silex in accordance with Broca's procedure. This way, he obtains a very wide hole on the outer table and a smaller one on the internal table. He criticises this procedure as the result does not resemble the trepanations that are commonly found. Afterwards, he comments Capitan's procedure, which allows to obtain a *'rondelle'* and which consists of hewing some straight or curved lines with the tip of a flint and going over these lines many times exerting a great force. This is a long procedure, as it takes more than an hour and leaves an opening with pronounced vertical edges. He points out that this opening is uncommon in the European skulls but more frequent in the Peruvian ones. Lucas-Championnière describes his own original trepanning method, which consists of carrying out several cranial drills by rotating an unsculptured flint. The drills reach the internal table and coaptate on the surface at the outer table. Once this phase is over, a slice of bone is lifted by leverage with a thin-edged stone, completing thus the trepanation. He describes in detail some Neolithic and pre-Columbian trepanned skulls in his book. He also describes and includes the image of a Kabyle skull from the North-East of Argelia with different types of complete or incomplete trepanations that were carried out postmortem. He considers that it was a model used to teach or to train the trepanation techniques.

Thomas Wilson Parry (1866–1945), an English physician, carried out a wide practical study by drilling and trepanning skulls using systematically the techniques and instruments that were supposed to have been used in the European Neolithic [2]. This is why he focused on the use

J. M. González-Darder, *Trepanation, Trephining and Craniotomy*,
https://doi.org/10.1007/978-3-030-22212-3_4

of the flint. In other experiments, the author carried out drills with shark teeth, flint tips, abrasions with flints and cuts with obsidian. He showed that each culture used the instruments available in their environment for trepanations and that each instrument made a hole of a different nature and size. Some of these beautiful skulls are exhibited at London's Science Museum and are available on the Internet.

In general terms, any new discovery of trepanned skulls in cultures in which there were no similar findings until then was accompanied by an experimental demonstration of the feasibility to carry out such trepanation with the materials and instruments that were available to them. Hence, a very recent study from Krivoshapkin and collaborators about the trepanations carried out during the fifth–third centuries BC in the Altai mountains of Siberia by the *'pazyryk'* civilisation can be used as an example to illustrate this working methodology according to the current scientific standards [3]. In that culture and at that time metal instruments made of iron, copper and bronze were available. However, no instrument has been found that could be unequivocally used in trepanations as well as no written evidences in this regard. The authors' working hypothesis is that metal instruments with the shape of knife were used in trepanations. The authors dismiss the use of iron instruments as in the magnetic resonance spectroscopy studies of the bone no ferromagnetic elements have been found on the edges of the trepanation. Instruments made of copper are too soft to cut or drill the skull; this is why they are rejected as well. Bronze is an alloy of tin and copper in variable quantities, but it is hard enough to cut or drill the bone. This is why they postulate that the instruments might be made of bronze. After several preliminary studies on animal skulls, the authors used a bronze knife (*'tagarsky'*) of that time which belonged to a museum in a final experiment in order to carry out a trepanation on a fresh modern human skull but the knife proved to be too soft and ineffective. Finally, the authors made a knife from a modern alloy of bronze with tin, copper and zinc. They managed to carry out a trepanation similar to the *'pazyryk'* in 28 min, at the expense of a great effort. The trepanation technique postulated by the authors would have two steps. The outer table would be removed in first place by a cutting, scrapping or abrasive mechanism with the bronze knife in a tangential direction to the surface of the skull. Once the diploe was exposed, they made shorter movements with a more vertical angle aimed at removing the cancellous bone and reaching the internal table. After being drilled, the internal table is easily removed or raised.

Due to the myriad of studies of this kind, different classifications according to the types and techniques of primitive trepanations have been carried out. However, there is some kind of general agreement concerning the most common methods. We are going to detail below the cranial trepanation techniques that are considered most probable and have been corroborated. They particularly include boring, connected burr holes, scrapping, polygonal cutting, bevelled cutting, circular grooving, cutting with leverage, tapping and drilling with a cylindrical object (Fig. 4.1). Some skulls show incomplete trepanations, i.e. for some reason the internal table has not been drilled. The reason cannot be determined as some of them show evidence of survival. Moreover, some trepanations could be carried out using a combination of two or more cranial drilling techniques. When an old trepanned skull is studied, only the final result of the intervention is appreciated, in addition to the added taphonomic changes. If the cranial opening is large and, for example, it seems to be made by scrapping, it is possible that the trepanation would have been initiated with boring or polygonal cutting, which can no longer be recognised in the available bone remnants. In the same way, a large trepanation may have eliminated a cranial tumour or infectious lesion or a linear or depressed fracture of small size.

However, some basic techniques of primitive trepanation are described that are depicted in Fig. 4.2 in a set of photographs of Peruvian trepanned skulls.

4.1.1 Boring

It is the most common technique and can be carried out with a tip of a stone that is hard enough

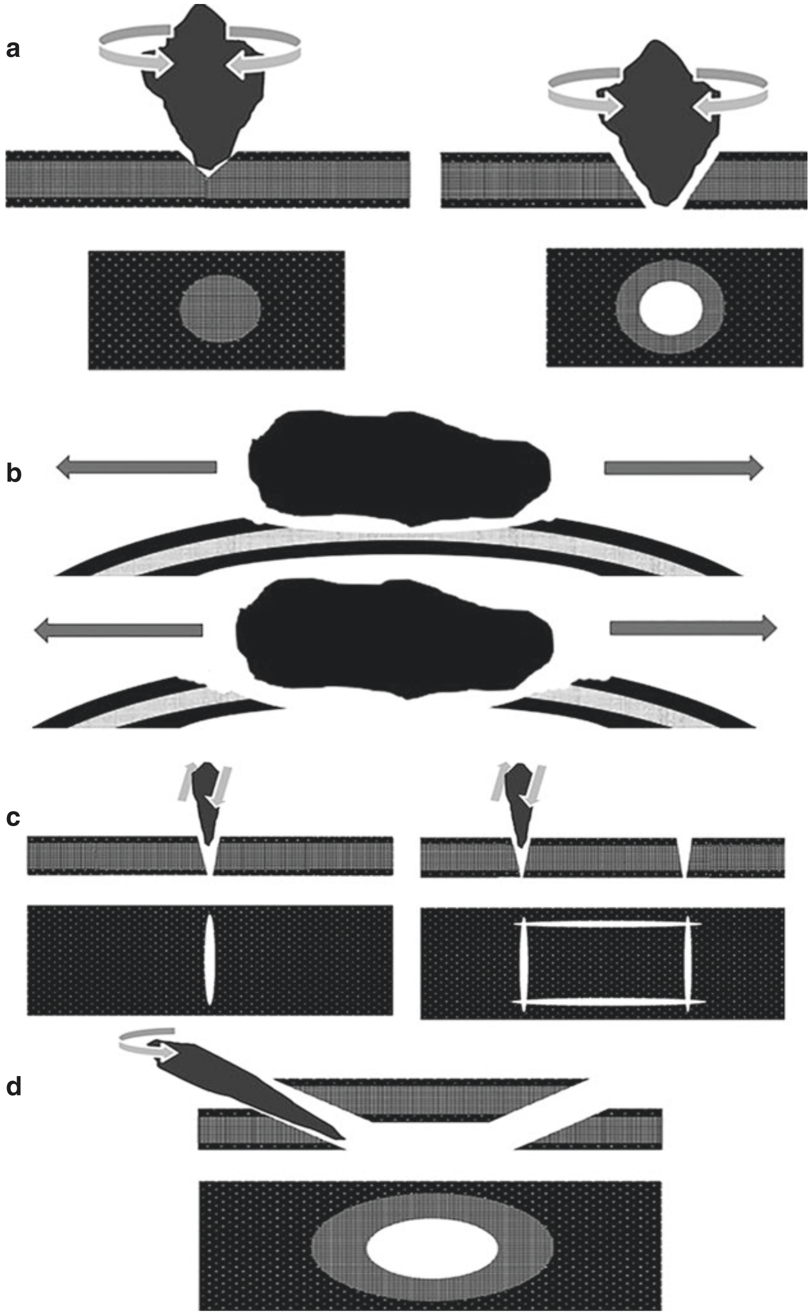


Fig. 4.1 Schematic representation of the different supposed techniques of cranial trepanation practiced by primitive cultures, particularly those used in the European Neolithic and in the pre-Columbian cultures. (**a**) Diagram of trepanation by boring. (**b**) Diagram of trepanation by scrapping. (**c**) Diagram of trepanation by polygonal cutting. (**d**) Diagram of trepanation by bevelled cutting

and that is held in hand or fitted on a shank. The trepanner performs half-angle rotation movements, getting to drill in the end the cranial vault. This rotating movement could be improved by mounting the handle on an acceleration system based on an arch with a rope. If the trepanation does not pierce the endocranium it will be considered an incomplete trepanation, in which the resulting hole has a conical shape, whereas if it surpasses the internal table it will be truncated cone shaped. In any case, the hole is always circular and has a wider diameter at the outer table than at the internal table of the skull. The inclination or slope of the edges of the hole is very pronounced and the distance between the outer and the inner margins is very short, although it

Fig. 4.2 Several Peruvian trepanned skulls and the alleged techniques used for trepanation. (**a**) Five perforations grouped in the temporo-occipital region of the skull. This technique of trepanation was not very often used in South America. The author of the image suggests that the holes were made using a small and sharp instrument and a curette (Revash 2, Amazonia region, Peru). (**b**) Connected small burr holes (*'corona de ebanista'* technique), showing signs of survival (Pampas, Peru). (**c**) Scrapping. Incomplete trepanation in a case of depressed skull fracture. The signs of scratching and scrapping are clearly visible on the bone (Paracas, Cabezas Largas, Peru). (**d**) Polygonal cutting. This skull shows three square trepanations using the same technique of polygonal cutting (Andes, Peru). (**e**) Bevelled cutting. This trepanation technique was common in South America. The trepanation shows signs of survival (Paracas, Cerro Colorado, Peru). (**f**) Circular grooving. This skull shows a probable post-mortem groove made around a trepanation. The trepanation shows no signs of survival and was carried out using the bevelled cutting technique (Aymara culture, Peru). (**g**) Skull with three small trepanations in the parietal bone done by bevelled cutting. There is a large area of bone erosion (Paracas, Cavernas, Peru) (courtesy of José María Fernández Díaz-Formentí)

Fig. 4.2 (continued)

depends on the shape of the instrument. The edge of the cut is clean and no evidence of scrapping is observed on the outer table around the hole, although it might show deflecting lines or microfractures. The materials that were supposedly more useful and common to carry out these types of trepanations were hard microcrystalline rocks, such as flint, chert or chalcedony. Other hard materials such as animal teeth or bones can obtain a similar result. However, fragile materials such as obsidian broke easily when used to bore.

4.1.2 Connected Burr Holes

It is a variation of the previous technique. Multiple small holes are made close to each other by boring and forming a circle. This way, they are all linked together in the end or so close that the bridges or fragments of bone between them break by tapping the area. In both cases, a scalloped disc of bone is removed. This method is scarcely observed. It is shown in postmortem trepanations, as it was probably used to obtain necklaces or amulets, or to practice or train the technique. Some skulls with this type of opening have been found in South America where the technique is named in *'corona de ebanista'* (cabinetmaker's crown).

4.1.3 Scrapping

To practice this technique a pimply or vitreous stone is required, such as a lithic core of flint, chert or chalcedony from which flakes have been removed and which has edges. The surface of the calvarium is sanded with the stone by making extensive swinging movements tangential to the surface of the skull. As this surface is curved, it finally allows to make a hole. The hole obtained is, in this case, ellipsoid and it is usually surrounded by an abraded area on the outer table. The minor the curvature of the skull is, the more extensive this area will be. In this case, the drill has a smaller size on the internal table than on the outer table. The edges of the hole have a scarce slope or inclination. This trepanation technique is the oldest and is assumed to have the highest survival rate, although the abraded area can be mistaken for an area of osseous regeneration.

4.1.4 Polygonal Cutting

This technique consists of making linear cuts that cross forming a polygon. The polygonal technique was practised with a flint or obsidian which was sculpted so that it had the shape of a knife. It consists of making one or more straight cuts by sewing movements. These cuts due to the curvature of the skull are fusiform shaped. In those case where they don't completely drill the skull, the Hispanic-American authors have compared its fusiform shape with an Indian canoe. The trepanation is polygonal when several cuts cross over. The most frequent one has a quadrangular shape. This method was scarcely used in Europe, although it was a pretty common technique in South America. Sometimes there is just a single fusiform groove or multiple grooves that do not complete a polygonal resection. When there is a complete polygonal figure, it is normally a square. The polygonal cutting allows to obtain a plate of bone, normally by levering from one of the grooves. This could cause to obtain incomplete cranial fragments or additional cranial fractures. This was the trepanation technique used on the skull that Squier brought from Peru.

4.1.5 Bevelled Cutting

To practise this technique a hard, cutting stone is required. A bevelled cut towards the centre of the opening is made on the surface of the skull. It reaches the internal table and creates there a central hole that is more or less circular or ellipsoid and which is surrounded by an extended, bevelled, abraded area with scarce slope. In this case, the drill has a smaller size on the internal table than on the outer table. When completing the trepanation, a slice of bone is lifted. It was practised in South America with obsidian stones. The scrapping and bevelled cutting methods can be difficult to distinguish on a trepanned skull, especially in those trepanations with survival evidence. However, the latter allows to obtain in the end a slice of bone and shows no abrasion evidence on the outer table and the edges are always more leaning.

4.1.6 Circular Grooving

Circular grooving consists of making a circular groove and lifting a disc of bone. To do so, a ring groove is hewed with a sharpened tip, going over the initial groove many times. The groove will be deeper and deeper until reaching the internal table. It can be broken by leverage at that moment, allowing thus to remove an osseous fragment or a more or less ovoid or circular slice. This was one of the supposed methods with which the *'rondelles'* were obtained.

4.1.7 Cutting with Leverage

It is not a very frequent method. One or two longitudinal cuts are made and the skull is fractured by leverage.

4.1.8 Tapping

The drill is carried out with a hard, cylindrical object made of wood, bone or stone which is tapped with a heavy object that acts as a mallet. This is an exceptional system.

4.1.9 Drilling with a Hollow, Cylindrical Object

It is carried out by rotating a hard, hollow, cylindrical object made of wood or bone and by means of abrasive sand. A cylindrical hole with vertical edges and a small, cylindrical slice of bone are obtained.

4.2 Pseudotrepanations

Skulls with holes, drills or windows of different sizes and shapes can be found in archaeological sites. Not all cranial openings that are found among such archaeological remains are, of course, authentic trepanations. In fact, the first step a palaeontologist takes when coming across a possible finding is dismissing the idea that it is a pseudotrepanation and not an authentic trepanation [4]. This is normally a hard job as in most cases, when finding a drilled skull in a site, the only information that is available comes from the osseous remain itself. However, nowadays we have a lot of information and a scientific methodology to face this first dilemma based on the data provided by the finding itself. Accordingly, it is necessary to briefly review the different types of pseudotrepanation.

Most of the trepanned skulls are obtained by means of exhumations. If the remains have been burnt or left exposed to the environmental elements, they are not adequately preserved. The burial involves preliminary ceremony rituals in any culture. These can influence the preservation of the remains. For this reason, we must consider in first place the changes on the cranial remain caused by the process of preparation for the burial. To do so, we must consider what is known about these rituals concerning the historical period of the site and the cultural context thereof. Exhuming the skull is a mechanical process. No matter how carefully it is done, as it always involves the need of handling the remains to disinter them, pack them up and take them to the laboratory. Finally, a palaeontological study is necessary as well as the preparation of the remains for storing to be exhibited at the museum, both meaning an additional handling.

The lapse of time between the burial and the exhumation of the skull is not exempt from the influence of the biological processes and the chemical and physical changes of the skull that can alter the remains. Moreover, the period of time along which the trepanned skulls are buried can last hundreds or thousands of years. The favourable natural changes of these processes lead to the fossilisation of the biological remains. This allows an indefinite preservation thereof. The study of the burial procedure, the decay and the preservation of the buried remains during its fossilisation process is a subspecialty of palaeontology called 'taphonomy' (from the Greek word 'τάφος' *taphos*, burial, and 'νόμος' *nomos*, law). This term was introduced by the Russian palaeontologist Ivan Efremov (1908–1972) in 1940.

The contamination before the burial can be due to several causes, normally due to human actions. Hence, among other intentional cranial drilling causes, it is possible to find skulls that were drilled postmortem to obtain osseous fragments which were used in time as pendants or amulets (*'rondelles'*). Other drills can be due to impalements of the heads with weapons, wooden stakes or metal bars to be shown as trophies or offerings. Finally, some skulls can be drilled in situations of nutritional cannibalism or in rituals. Sometimes part of the cranial remains can be missing upon the burial as a consequence of losses due to the cause of the death or upon the preparation process of the corpse. After burying a complete skull, there are several natural taphonomic agents that can cause drills on the skull, such as the position, action of the surrounding geological material, climatic elements, animal bites (particularly rodents), chemical or biological processes causing erosion, abrasion, corrosion, crushing or fractures on the bone. During the excavation and exhumation of the remains, human taphonomic actions can happen, such as accidental holes made by picks or blunt objects. Osseous material can also be accidentally lost throughout the cleaning processes and remain unnoticed. These deleterious actions caused by humans are more likely and serious when moving the remains to another place or exhuming corpses without an archaeological or palaeontological control, particularly when moving the remains before the archaeological exhumation.

A second cause for pseudotrepanations would be the existence of a premortem cranial damage that mimics the trepanation [5–7]. The skull can be opened due to genetic causes (cranial dysraphism, persistent parietal foramen), as well as tumours (benign or malignant intracranial or cranial tumours that get to erode the skull; they can be either primitive or metastatic), osseous infections (eosinophilic granuloma, tuberculosis or pyogenic infections) or metabolic diseases, although such pathological conditions are easily recognised as they are often associated with lesions in other bones of the corpse. Traumatic injuries with all types of fractures that are due to war wounds are one of the most frequent reasons causing confusion. In this regard, if we know the war weapons used in that time or if they are available it is possible to match the number, size and shape of the injuries with the weapon involved. This allows us to discard those trepanations that are actually fractures caused by direct impact with a weapon or a blunt object (Fig. 4.3). A very particular cause of confusion is the so-called growing fractures. These are linear fractures of the skull in children that are normally associated with a break in the dura mater. In some cases, due to the child's growth of the skull the fracture does

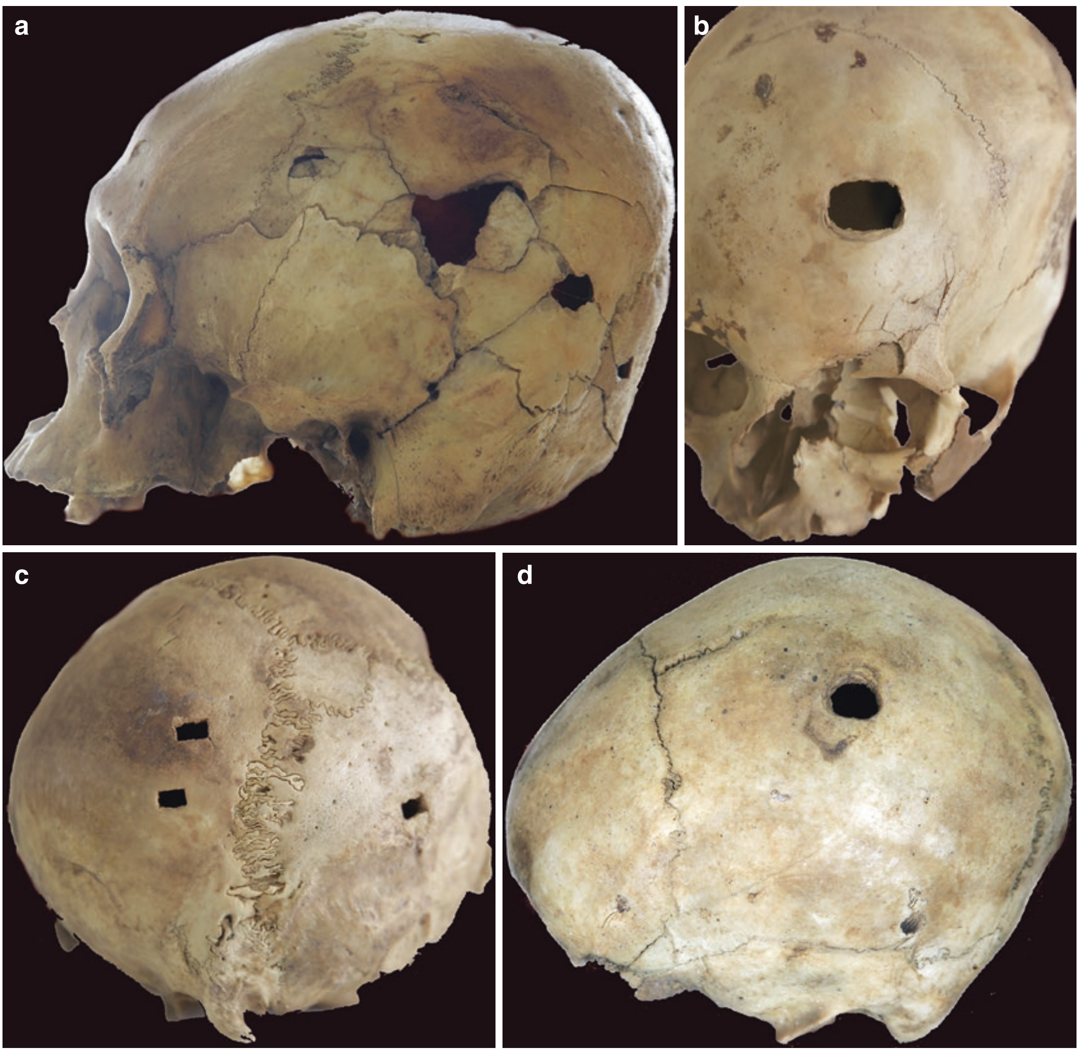


Fig. 4.3 Pseudotrepanations due to weapon injuries. (**a**) Compound left parietal fracture made by a round stone truncheon (Puruchuco, Peru). (**b**) Left frontal quadrangular fracture made by a star stone truncheon (Puruchuco, Peru). (**c**) Skull with three small quadrangular fractures made by spears (Mochito, Peru). (**d**) Gunshot round left parietal fracture made by a harquebus (Puruchuco, Peru) (courtesy of José María Fernández Díaz-Formentí)

not adequately close, allowing thus the arachnoid membranes to herniate along the cranial dural breach (leptomeningeal cyst). This herniation keeps the cranial defect open indefinitely, making it wider and wider. It will even persist on the patient's skull during adulthood. These types of cranial defects are normally long, have round edges and are mainly shown on the parietal bones.

Finally, we must consider as well the mistaken interpretations provided by researchers, palaeontologists and forensic archaeologists. Many skulls that were considered trepanned upon their finding have been reclassified later, after being studied again. Nowadays those skulls that were supposedly trepanned are studied with imaging techniques that include conventional X-rays, computed tomography with 3D reconstruction and nuclear magnetic resonance. Magnetic resonance spectroscopy studies are also carried out to find, for example, traces of chemical elements or compounds that suggest the use of metal instruments or tools with metal alloys during the trepanation. However, primitive trepanations might be over-diagnosed. Hence, there is an explainable scientific perversion causing the palaeontologists to assume that even the smallest depressions found on an exhumed skull are incomplete trepanations. They sometimes even have the audacity to consider them as trepanations with survival signs, turning a routine finding into a relevant one deserving a scientific publication. It is also easy to consider an osseous defect as a trepanation if there are already documented trepanations in the same site or culture. When reviewing the images of these publications from a neurosurgical point of view, a great number of these findings might be considered just depressed fractures caused, for example, by a hard-piercing object. Domènec Campillo (1927–), an important reference in the field of the Spanish palaeontology and also a neurosurgeon, thoroughly discusses this topic on a review article from the *Actas del VII Congreso Nacional de Paleopatología*. In fact, it is possible to find examples of dubious interpretation in this proceedings book in some of the works that were presented at the Congress and that were gathered in the book [8]. John W. Verano, an American professor of anthropology at the Tulane University and a worldwide opinion leader on this topic, also discusses this issue. He agrees on the difficulty of the differential diagnosis between a real trepanation and those cranial defects caused by other mechanisms and the possibility of classification mistakes [6]. As an example, a recent paper describes an infratentorial mastoid trepanation whereas in fact what the images suggest is that it could be the osseous foramen of a huge mastoid emissary vein. This possibility is not even considered by the authors in the differential diagnosis of the foramen [9]. Another paradigmatic example, but in the opposite direction, is that some Neolithic trepanned skulls were considered ceremony vessels for ages, i.e. pseudo-trepanations, although this concept did not exist before Paul Broca suggested in the second half of the nineteenth century the possibility that primitive peoples trepanned the skull of alive persons and that some of them could have survived.

Therefore, just like any other scientific data, a drilled skull must undergo thorough scientific studies to be classified as a trepanned skull. In addition, new studies can reclassify a trepanned skull and take it back to the pseudotrepanned category or vice versa at any time.

4.3 Incomplete Perforations of the Skull and *'Rondelles'*

Archaeological studies have revealed skulls that unequivocally show human pre- or postmortem handling thereof and which are different from the conventional trepanations. We do not include among them those cranial deformation techniques with aesthetic or religious purposes, but the destructive manipulations with discussed or unknown aims.

We now review two types of intentional handling of the skull of alive individuals without the aim of drilling it. However, they occasionally produced a complete or incomplete cranial hole. This is why they are not considered authentic trepanations. In particular, we are going to focus on the so-called pre-Columbian supra-inion trepanation and the European Neolithic sincipital-T.

The ‘supra-inion trepanation’ is a particular way of intentional handling of the skull which consists of performing a simple scrapping of the periosteum of the outer table of the skull, in the supra-inion region. It could exceptionally reach the internal table, making thus a hole on the skull. The scrapping was performed on the middle line, above the inion and the superior nuchal line and below the craniometric point lambda (Fig. 4.4). From a craniometric point of view, the inion, which normally corresponds to the external occipital protuberance of the occipital bone, is the cranial point in which the median sagittal plane concurs with the occipital line or superior nuchal line. This line is the place of insertion for the aponeurosis and the most superficial nuchal muscles of the nape of the neck. The external occipital protuberance is made up of the insertion of the nuchal ligament and can be very variable in size depending on its strength. The internal

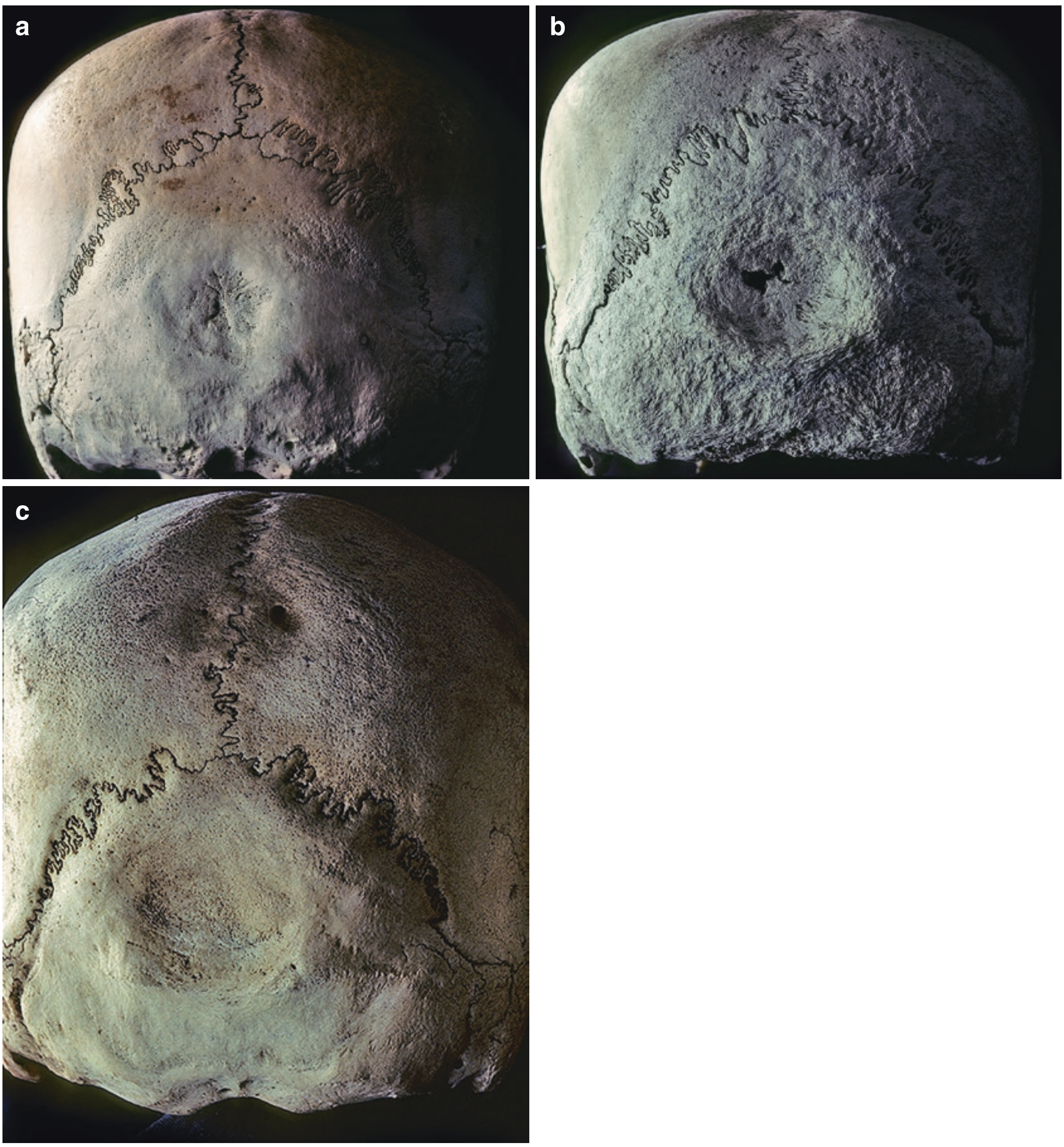


Fig. 4.4 Peruvian supra-inion trepanations (**a**–**c**) (images courtesy of the author José María Fernández Díaz-Formentí)

occipital protuberance is approximately 1 cm more caudal, on the inner or cranial side of the occipital bone and corresponds to the torcula or torcula Herophilus. The opistocranium, which is the most prominent area of the occipital bone along the middle line, can be found on the middle line above the inion. It marks the largest antero-posterior diameter of the skull. Lambda, which corresponds to the junction of both lambdoid or parieto-occipital cranial sutures, is also located near this point.

In mummies with preserved soft tissues, it has been proved that osseous handling was performed through a horizontal incision. Apart from those remains suggesting an osseous scrapping, the skulls show a new superior nuchal line that is rougher and more caudal than the physiological one that was previously described. Many of these skulls have also deformations caused by bandages and boards. This practice was carried out in Peru (particularly in the Chancay and the Chimu cultures) and Mexico (Chiapas, Yucatan). The incidence of the supra-inion trepanation was very high among the population, as skulls of different ages and both sexes have been found. At first, experts assumed that it was the indirect consequence of bandages causing skull deformation or any other type of dressings. However, the evidence relating the incisions on soft tissues in mummies makes us now think that the so-called supra-inion trepanation was an intentional intervention. It probably had a prophylactic purpose to enable the use of deforming bandages (or other type of dressings). Alternatively, it could have an unknown cultural or ritual aim.

The so-called sincipital T mutilation is also an intervention on the periosteum and the surface of the skull that is similar to the previous one but with lower intensity. It does not aim to drill the skull either. It was described for the first time in 1895, in France, by the anthropologist Léonce Manouvrier (1850–1927) in six Neolithic skulls. Similar interventions have been found in other primitive and developed cultures. Its incidence is very low. It has been evidenced in brachycephalic skulls, particularly in children and women. This deformation consists of a T-shaped osseous depression on the middle line. The vertical arm appears along the sagittal suture and the horizontal one extends throughout both parietal bones, usually near the lambdoid or parieto-occipital sutures. Its meaning or justification is not known but it was used between the sixteenth and seventeenth centuries in Europe to treat certain mental disorders and alleviate headaches. It was carried out by cauterising the periosteum and/or the bone without the aim of drilling it.

Some trepanation techniques enable, as a result of the trepanation itself, to obtain detachable pieces of the skull with different sizes and shapes. They were usually round, disc shaped but sometimes they were polygonal. This might (or not) be the reason why it was absolutely necessary to bore in order to obtain them. It has been proved that some of these osseous fragments (*'rondelles crâniennes'*) were subsequently used as ornaments or amulets. Actually, some *'rondelles'* show one or several small drills so that they could be strung with a cord and worn as necklaces. Some skulls have been associated with two trepanations. One of them had survival signs whereas the other had no survival signs or the trepanation was postmortem. This suggests that the second trepanation was used to obtain discs of bone that were subsequently used as ornaments or, particularly, amulets as they came from an individual who had survived a trepanation. On the contrary, there are trepanned skulls with a *'rondelle'* from a different skull that was inserted inside the osseous defect.

P. Barthélemy Prunières (1828–1893), a physician of the town of Marvejols (Lozère, France) and father of the palaeopathology, presented in 1873 in Lyon before the French Society a parietal bone exhumed from the dolmen of Lozère with a piece of bone that clearly belonged to a different individual inserted therein. Other findings were added subsequently. Prunières called them *'rondelles'* due to their constant round shape, although the trepanations had more irregular edges. He hypothesised about the idea that placing skull fragments from another person inside a trepanned skull was clearly due to magical reasons.

The *'rondelles'* found in France are almost the only ones that comprise the whole thickness of the skull, i.e. the three layers of bone of the cranial vault. Other discs with the same purpose found in different sites only have the outer table. They were probably obtained postmortem by means of spinning a cutting compass as there are evidences of multiple grooves or incomplete discs in some skulls.

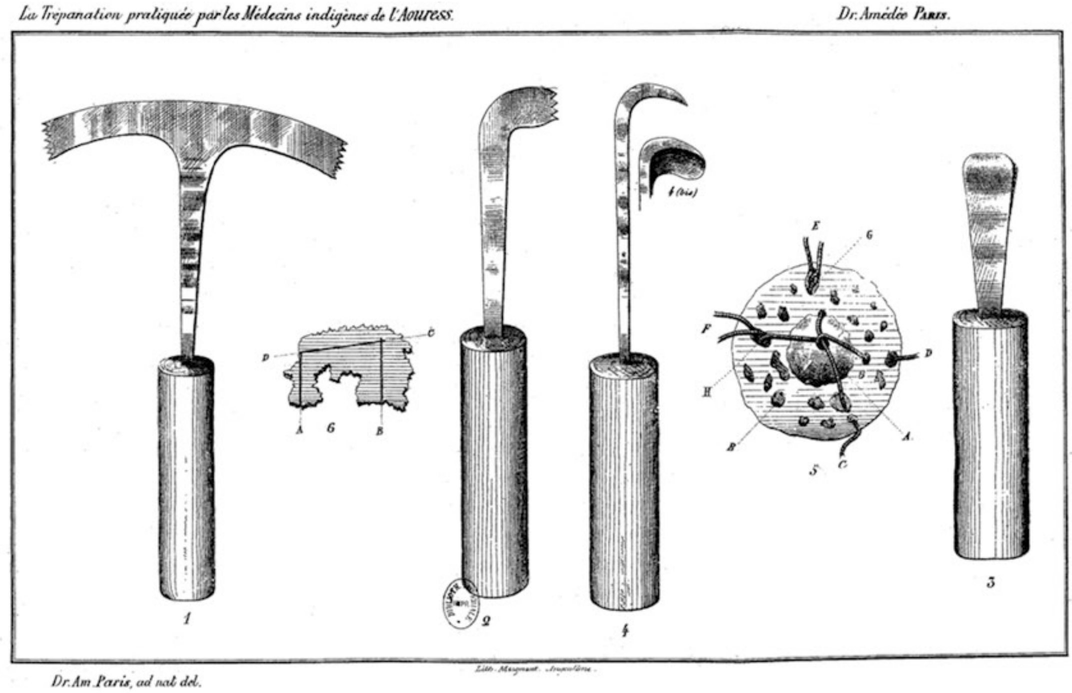
4.4 Materials and Tools for Trepanning in Primitive Cultures

The materials used in ancient primitive cultures for trepanning have been mainly stones, particularly flint and obsidian. The flint, as well as chert and chalcedony, are rocks rich in silica and with microcrystalline structure, which confers them great hardness (flint: 7 in Mohs scale). They are all abundant rocks and the difference among them is of geological nature. However, for all practical purposes, they are all equally useful for trepanations by boring or scrapping, or even by cutting. On the contrary, obsidian is an igneous rock that belongs to the group of silicates. It is also very hard (5–6 in Mohs scale) but when it is fractured it shows rather hard edges that are very sharpened. This makes it very useful in trepanations by boring or cutting. It has been proved that it is possible to trepan the skull with animal teeth, horns or bones, or even with hard wood. Some later primitive cultures had access to metal materials, but the alloys that were available were of poor quality for trepanations, although they might be useful for soft tissues. In pre-Columbian Peru, the classical cutting instrument was the *'tumi'*, which was made of an alloy of Inca bronze or *'champi'*. Other later European civilisations also had bronze knives. In this context, we have mentioned the Siberian trepanations before.

On the contrary, contemporary primitive cultures use metal instruments made of steel (even surgical steel) for trepanations (Fig. 4.5). Amédée Paris described the instruments used for trepanation by the Berber people from the North of Africa in his monograph *'Mémoire sur la trépanation céphalique pratichée par les médecins indigènes de l'Aouress'*. The instruments were metallic and had a wooden handle. The author reconstructed them based on the original ones, as the owners thereof considered that they were sacred and did not donate them [10]. A reproduction of the actual instruments used for trepanation is collected on a plate of the book. The list of instruments is very short and comprises double saw, simple saw, straight elevator and curved elevator. In the plate there are draws of the external protection the trepanner used to employ to protect the cranial defect until the complete healing of the wound. This is a holed leather plate, with several wool strings passed and knotted to the plate. The plate includes also a draw of a bone plate rose from the right parietal bone. The bone segment has an anfractuous orifice secondary to a *'caries'*, by which the operator introduced a curved elevator.

In the same way, F. Terrier and M. Péraire in their entitled *'L'opération du trépan'* collet the instruments for trepanation practised by peoples of North Africa. Instruments are also metallic with wooden handle and different sizes and shapes. The list of instruments includes convex blade knife; hook spatula made with a spoon handle; clamp fastened with a leather strap; stiletto, which can be used as a cautery; razor blade; hook scraper; hooks with a wool pellet to remove the blood; double hook; three saws with long teeth; small straight saw with intermediate teeth; two small straight saws with fine teeth; four scrapers (*'brimas'*); two scrapers; and, finally, double hook that serves as a retractor [11].

Trepanations are the result of drilling the bone. Whether they were premortem or postmortem they required managing and controlling other aspects that were related to the procedure. These requirements were, of course, stricter in those trepanations carried out on alive individuals. In this regard, the handling of soft tissues during the opening and closure was more speculative than the techniques and technologies of the trepanation, as well as the analgesia, haemostasis and prevention of infections, particularly in ancient civilisations. Some pre-Columbian mummies show linear or star-shaped cuts on pericranial soft tissues (Fig. 4.6). Some contemporary primitive cultures carry out circular or square resections of the whole pericranium. Knotting the hair, suturing with thread and needle, applying heads ants or just a compressive dressing could make the



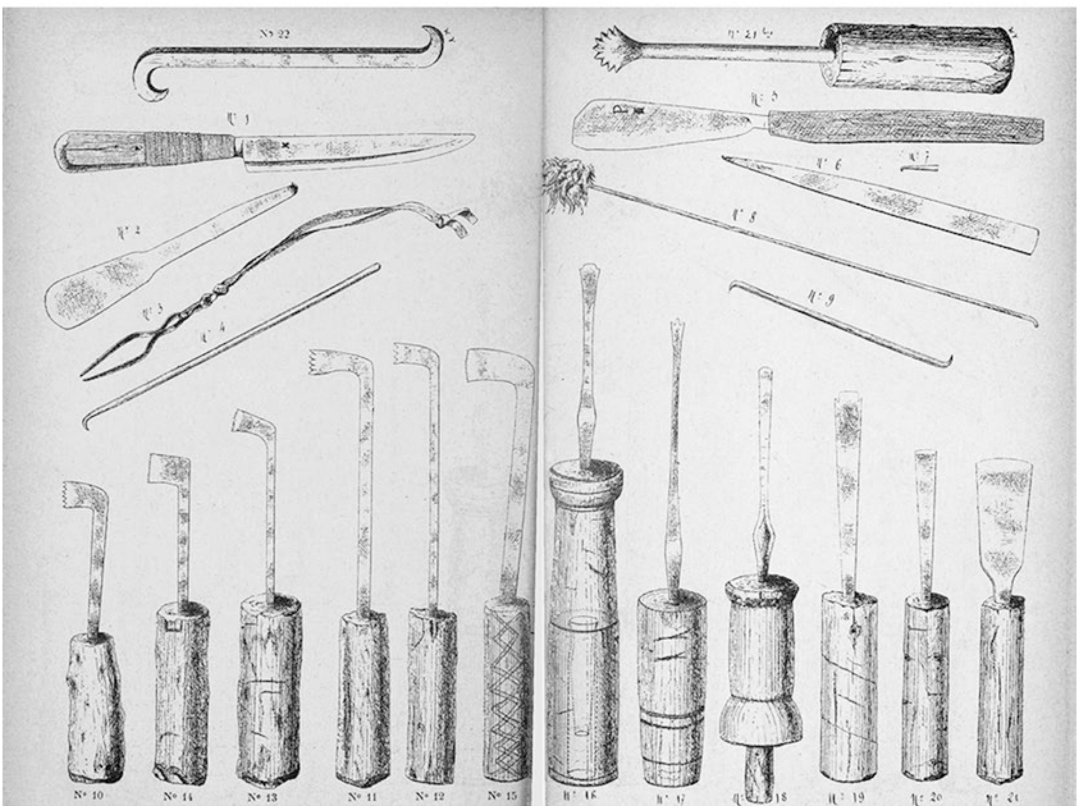


Fig. 4.5 Instruments used for trepanation by the peoples of North Africa according to Paris (upper) and Terrier and Péraire (lower) (Paris A. Mémoire sur la trépanation céphalique pratichée par les médicins indigènes de l'Aouress. Paris: Chez Adrien Delahaye; 1865; Terrier F, Péraire M. L'opération du trépan. Paris: Félix Alcan; 1895)

Fig. 4.6 Peruvian mummified heads with soft-tissue incisions and different trepanations. (**a**) Mummified head with a longitudinal incision of 13 cm and an incomplete trepanation. There are multiple complete and incomplete cranial perforations, and two perforations (Huarochirí-Yauyos, Peru). (**b**) Mummified head with a cruciform incision and an incomplete trepanation (Sierra Central, Peru). (**c**) Mummified head with a large star incision and a trepanation made by the *'corona de ebanista'* technique (Tantamayo, Huánuco, Peru). (**d**) Mummified deformed head with a frontal cruciform incision and a complete trepanation (Paracas, Peru) (courtesy of José María Fernández Díaz-Formentí)

closure. An alternative option consisted of leaving the wound open so that it closed by the secondary intention method. It is speculated that hallucinogens or alcoholic drinks were used for analgesia. However, none of them were most likely used. The use of antiseptic methods is not clear either, as primitive cultures are well known for being resistant to wound infections. In fact, there are very few trepanned skulls with survival evidence associated with osseous infection signs. We will later describe the accounts of direct or close witnesses of contemporary primitive trepanations. They include some revealing solutions for these issues.

As an interesting neurosurgical fact, there are two descriptions included in literature about trepanations carried out on alive individuals during the twentieth century by neurosurgeons. The patients suffered from a neurosurgical intracranial pathology and the neurosurgeons used sterilised pre-Columbian trepanning instruments. This proved that it is possible to successfully carry out craniotomies with these instruments. The cases were summarised by Marino and Gonzales-

Portillo in the journal *Neurosurgery* in the year 2000 [12]. We will proceed to describe them below.

In 1944 two Peruvian neurosurgeons carried out a trepanation using instruments from the Archaeological Museum of Cusco on a 22-year male who suffered from a cranioencephalic trauma after a tree fell down onto his head. They cut the scalp using a *'tumi'*, which also worked to lift the periosteum. They also used a sterilised Inca chisel made of obsidian to open the bone, achieving thus an oval craniotomy of 6x3 cm. The edges of the wound were sutured with an Inca bronze (*'champi'*) needle. The procedure took an hour. The patient died 7 days after due to a bronchopneumonia.

Two other Peruvian neurosurgeons, Graña and Rocca, carried out an experimental trepanation on a corpse in 1953. They made a 3 cm cut on the scalp with an Inca *'tumi'* and drilled the bone with an obsidian knife from Lima's National Museum of Archaeology and Anthropology. They noticed that obsidian knives broke when they performed circular movements to drill the bone and that the best trepanning technique with the obsidian instruments was making sewing movements. This way, they achieved a craniotomy with a quadrangular shape. Afterwards, they carried out a trepanation on an alive individual with these same instruments in 1953. The patient suffered from a cranioencephalic trauma followed by hemiplegia and aphasia. After being anaesthetised and intubated, the patient underwent a trepanation with the sterilised Inca instruments. A *'tumi'* was used to cut the scalp and a flint chisel to carry out the craniectomy, which had an oval shape. After exposing and opening the meninges, a subdural haematoma was successfully evacuated and the patient showed a satisfactory evolution.

Nowadays there are not too many doubts about the materials and methodologies used in these trepanations [13]. It is well known that it is possible to carry them out with lithic materials, as there are many documented experimental studies that prove it. We have also reviewed the different trepanning techniques, which are well described. They have also been reproduced in many experimental studies. In addition, the craniotomies that were successfully carried out in Peru by neurosurgeons using the materials and techniques employed in the pre-Columbian period evidence that they can be performed by skilled and trained people.

If we take into consideration the geographical and chronological isolation among the different cultures that carried out trepanations, we can affirm that the materials and technical solutions were autonomously invented in each culture. Cultures did not contaminate or teach each other the different methods. A decisive aspect was the specific lithic material that was available in the geographical environment of the trepanning culture or whether they could be provided with that material thanks to their trading activities. Hence, microcrystalline rocks, such as flint, chert or chalcedony, are particularly useful for techniques like scrapping or boring and they were used in Europe, as there was plenty of them. On the contrary, obsidian was used thousands of years later in America as it allows cutting techniques. Other Polynesian cultures used shark teeth and other available materials, such as volcanic glass or obsidian. Metals and primitive metal alloys, such as copper or bronze alloys, are clearly unable to drill the bone. Other more modern or contemporary cultures include metal instruments made of iron or steel among their materials, or even modern surgical instruments. Hence, if the geographical and chronological isolation of the main areas where trepanation was practised made it impossible to consider any process of teaching or knowledge exchange, each culture's preferences for a specific method suggest that the general solutions were very similar, as they got to use the same instruments. A key aspect was the type of drilling material that was available. The alternative to this hypothesis is the 'diffusionism' model, which has already been dismissed at least for those European Neolithic and pre-Columbian American cultures.

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5 The Question of Survival in Primitive Trepanations

A basic element when assessing the trepanned skulls of primitive cultures is the person's evidence of survival. This can only be studied by the pathological changes of the edges of the trepanned bone, particularly by the evidence of osseous regeneration. Of course, it is impossible to find such evidence in case of surviving a very short time or in postmortem trepanations. Likewise, the lack of evidence of survival cannot prove whether a trepanation was carried out shortly before or after dying. Regarding the primitive trepanations, the problem is that these changes must be shown on the osseous remains that are fossilised or, in any case, have experienced intense taphonomic modifications.

5.1 Biological Criteria

In this regard, Lastres and Cabieses describe some stages in the osseous regeneration process in those cases with survival [1]. If there are no signs of biological reaction of any kind on the skull or if the physical or mechanical signs that resulted from the trepanation are observable, it can be stated that the death was immediate or that the trepanation was carried out after dying. A superficial ring of osteoporosis appears between 1 and 4 weeks after surviving the trepanation. This ring is due to the hyperaemic reaction of the periosteum, which diffuses the mineral salts of the area. The necrotic remains of the bone existing along the edges of the bone and the wound disappear afterwards. This osseous necrosis is a consequence of the mechanical action of the trepanation itself or due to the devascularisation of the bone caused by the removal of the periosteum. If the person survives enough time, the necrotic bone will disappear due to the physiological resorptive processes. At first these remains become isolated forming some kind of 'sequestrations' that give the bone a moth-eaten look. They end up disappearing in full ('bone resorption' stage or 'osteolysis'). Several processes can modify this biological sequence, such as local infections, dressing change procedures of the wound, or cleaning actions when obtaining and handling the remains during the exhumation process or preservation at the museum. At this stage the edges of the bone are irregular and blurred. The initial line of the trepanation cannot be distinguished. If the trepanned person keeps surviving, the resorption of the osseous sequestrations ends and the 'bone remodelling' stage starts. In this stage the edges of the trepanation harmonise, round, and, due to the bone resorption on the trepanation margins, the diameter of the osseous defect that was initially created has become wider. At the bone-remodelling stage, bone starts to form between the internal table and the outer table of the skull. This requires a period of time of about 8 weeks. The ossification of the scar fibrous matrix that was formed starts now by precipitation of mineral salts. This way, bone is

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finally produced by forming radial striations and the edges condense. An irregular bone callus placed between the outer table and the internal table will seal at the end the edges of the skull. This way, the cranial hole will be round, hard and mineralised but the diploe won't be seen. The diameter will still be greater than the initial one and the bevel persists, as the outer table is reabsorbed more intensively than the internal table. There can be areas of deep heterotopic ossification above the dura mater but the osseous defect never closes, achieving thus a stage of stability. The lack of closure of the osseous defect is due to the lack of osteogenic stimulation, as bone formation takes place equally under compression or mechanical distraction stimuli according to Wolff's law. Contrary to the fractures in other bones, these stimuli do not exist in the skull and the process stabilises some months after. Therefore, these processes require months of survival. This evolutive sequence is illustrated in Fig. 5.1, showing the macroscopic changes in a set of Peruvian trepanned skulls [2].

John V. Verano establishes an easier classification in three stages [3]. During the first stage there are no cicatrisation signs and only the clean edges of the trepanation are evidenced. During the second stage there are osteoclastic modifications surrounding the areas of necrotic bone. Finally, during the late cicatrisation stage, it is possible to observe large areas suffering remodelling and harmonisation of the edges of the trepanation.

Regardless of the classification followed, the main problem has to do with the difficulty of evidencing these pathological elements on the fossilised biological remains, even with the use of modern imaging techniques (including computed tomography and nuclear magnetic resonance). Even with these limitations, the validated evidence shows a very frequent and high survival rate, more than 75% of the trepanned cases in some studies. The infections subsequent to the trepanation had a rather low incidence, but the evidence thereof means an unequivocal sign of survival.

5.2 Radiological Criteria

Nerlich and collaborators addressed this topic with some modern skulls that were subjected to surgical craniotomies with bone flap reposition and with different survival times [4]. They confirmed that the changes in the healing and bone remodelling processes depended indeed on the time. The authors did not find any osseous reaction on the skulls of patients who survived hours or days. They could not find any evidence of osteoclastic reabsorption of the bone or bone formation either. A case with 2.5 months of survival showed signs of bone resorption with thinning of the cutting edges on the bone and some weak joints between the skull and the bone flap. In those cases, with a longer survival, the signs of osseous fusion are increasingly large and evident, although they are never complete. They are always associated with a thinning of the cutting edges on the bone, both on the skull and the flap sides. These cases with long survival times also showed calcified plaques adhered to the dura mater. On the contrary, there was no osseous filling of the defect in any of the cases in which the bone flap was not repositioned, remaining thus the hole open. The edges of the skull had also experienced some thinning and the structure of the diploe could not be recognised. Our own observations on neurosurgical patients who had been re-operated are in line with these considerations.

We have also studied different evolutive imaging studies after surgical craniotomies with no reposition of the bone flap and skull fractures and the results are shown (Fig. 5.2). Neurosurgical craniotomies were made with a high-speed motor saw, without replacement of the bone flap, without wound complications and with different follow-up times. The first row of the figure shows axial computed tomographic cuts made 48 h, 3 months and several years after the craniotomy. In the second row, coronal cuts made with the same chronology are shown. In the studies done 48 h after the craniotomy (left), the bony edge of the cut can be seen with the external table, diploe

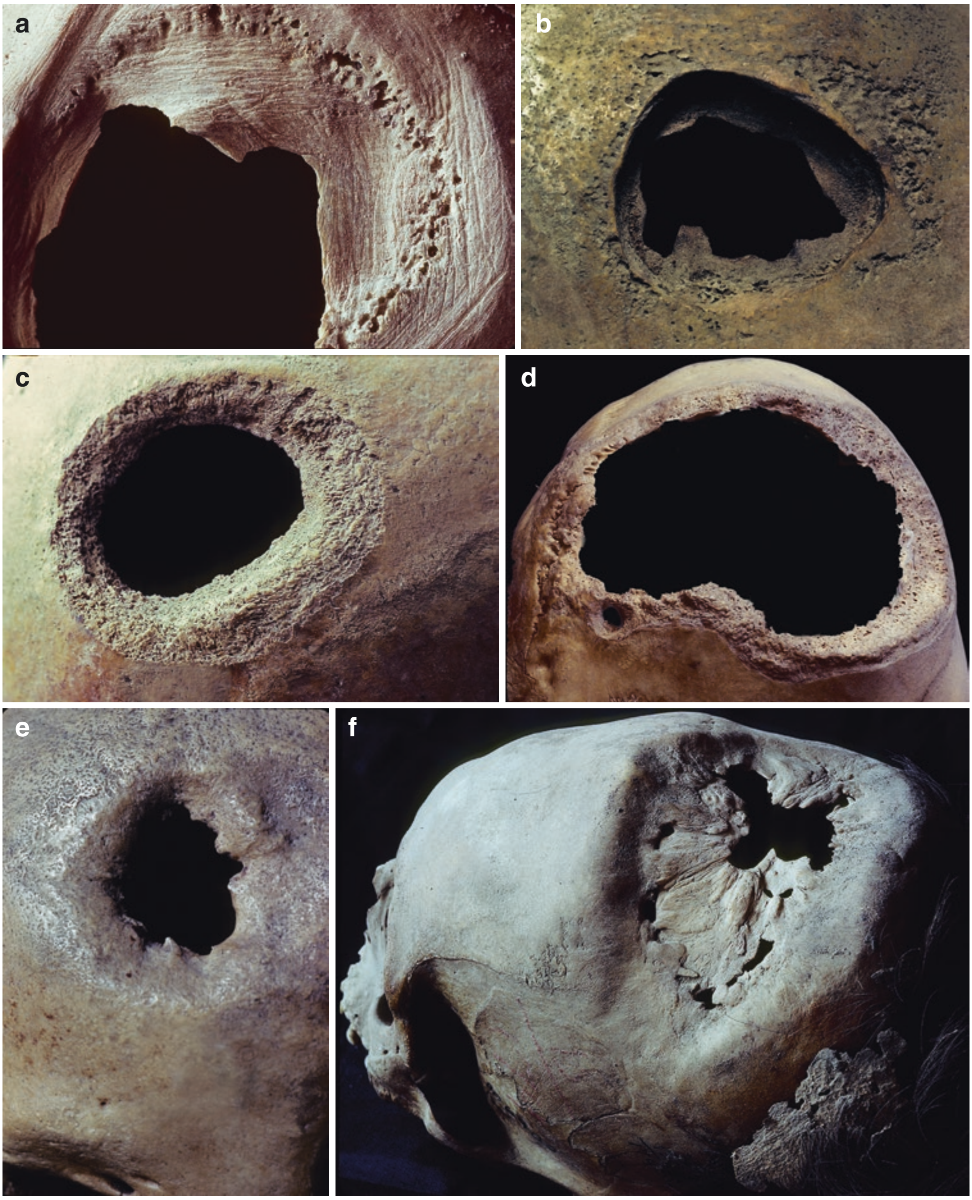

Fig. 5.1 Survival signs after primitive Peruvian trepanations. (**a**) No survival or very short survival (less than 1 week). The signals of the raspatory instruments are clearly seen in the internal and the external table of the skull and the spongiosa of the diploe is also clearly seen. There are no signs of bone changes (Paracas, Peru). (**b**) Short survival (between 1 and 3 weeks). There is a rim of devitalised bone around the hole and a second more peripheral layer of bone showing osteoporotic changes (Paracas, Peru). (**c**) Short survival (between 1 and 2 months). The initial hole has enlarged because the necrotic and devitalised bone has been lost (sequestra) (Paracas, Cerro Colorado, Peru). (**d**) Short survival (between 2 and 3 months). The rim of the hole becomes more regular because the necrotic bone has almost completely disappeared and the regeneration changes of the bone begin, forming small bone bridges all around the free edge of the rim (Paracas, Peru). (**e**) Long survival (more than 4 months). The slope of the rim becomes very flat because of the reabsorption of the external table of the bone. There is also a new bone growing between the external and the internal table forming a layer of compact bone that closes the spongiosa. Some new bony layers can be growing in the bottom of the hole (Revash-2, Amazonas region, Peru). (**f**) Very long survival. Changes in the bone are stable and there is a great amount of new bone in the bottom of the opening, formed probably by the help of the remains of the internal layer of the skull (incomplete trepanation), bone sawdust, chronic inflammatory response of the dura mater or pericranial soft-tissue scar (Paracas, Peru) (courtesy of José María Fernández Díaz-Formentí)

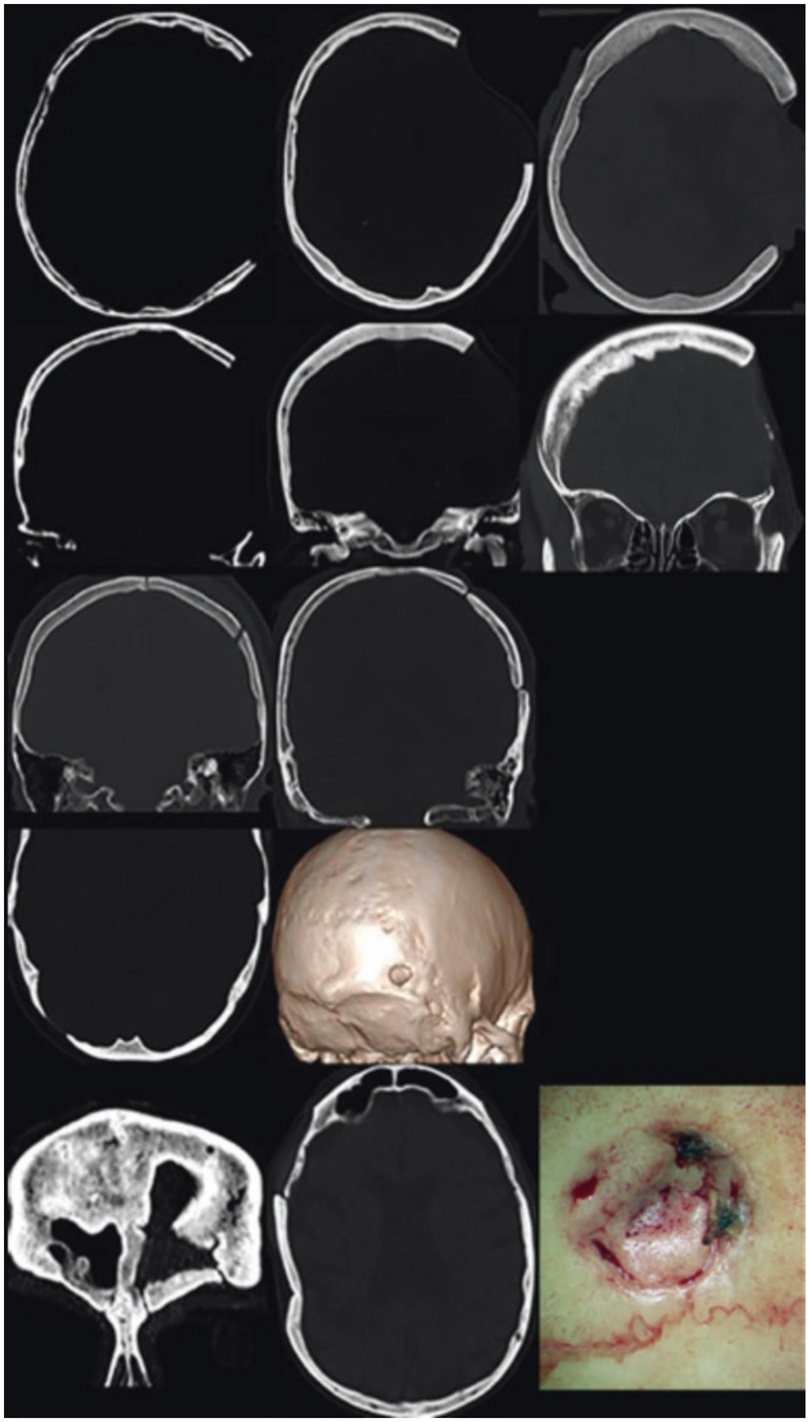

Fig. 5.2 Skull computerised tomography studies with bone window in several patients, with different types of modern cranial opening, all of them without wound complications and with different follow-up times. For a precise description see the text

and internal table well differentiated. In the studies done at 3 months (centre) the reabsorption of the cancellous bone of the diploe is observed at the cutting edge of the craniotomy. The studies carried out years later (right) show that the edge of the bone is rounded, with a new compact bone border that extends between the outer and inner table of the skull. In this particular case there are signs of calcification or ossification of the dura mater within the bone defect. In the central row of the figure there are two studies in patients who have undergone surgical craniotomies with a high-speed motor and replacement of the bone flap. The study on the left is 48 h after surgery and the one on the right was done years later. The findings are similar to those described above. It is remarkable that there is no new bone between the bone flap and the edges of the craniotomy. The following study corresponds to a 28-year-old man who underwent a right occipital epidermoid tumour resection at the age of 14. The edges of the hole are remodelled with compact bone growing between both tables of the skull. Again, there is no bone formation in the small skull defect. A computed tomography scan and 3D reconstruction of the fine-cut CT scan are shown. The lower row shows scans of fractures secondary to head injuries that were not surgically manipulated. The left one corresponds to an adult patient with a fracture of more than 20 years of evolution of the left frontal sinus, without signs of fusion but with signs of bone remodelling at the edges of the fracture line. The second corresponds to a nonagenarian patient who suffered a depressed cranial fracture more than 40 years before, not surgically repaired, showing the typical signs of survival, with some bone fusion between the fragments. In the area without bone fusion the resorption of the external table is evident as well as compact bone formation between the external and internal tables. The last figure of the lower row is an intraoperative picture of a burr hole done 3 years before in the frontal bone just anterior to the coronal suture. The hole was filled with the bone sawdust obtained in the trepanation. In this case, the hole is partially filled with new bone and the dura mater is not visible.

After performing a craniotomy, the edges of the bone thin over time, especially on the outer table. In the end, a layer of compact bone is formed in such a way that it covers the diploe and spreads between the outer table and the internal table. We have never observed the complete and solid closure of the osseous defect. The existence of relevant calcified plaques on the external layer of the dura mater is an exceptional phenomenon.

However, the observations of bone remodelling on a current surgical craniotomy cannot be extrapolated to the trepanations carried out in primitive cultures as there are important variables that make it impossible to compare them. Therefore, the cutting conditions of the bone in modern studies are completely different when they are compared with any of the methods that were supposedly used in primitive trepanations. In modern craniotomies, the bone sawdust (an important element for osseous regeneration) is systematically cleaned and removed. Hence, osseous regeneration is not as complete in modern craniotomies as it was in primitive trepanations. The craniotomy technique avoids the attrition of the dura mater, and dural cicatrisation should be an element favouring a subsequent ossification. The preservation of the dura mater was impossible with many of the trepanation techniques used by primitive cultures. The dressing changes, the materials and substances applied on the wounds and the general conditions for cicatrisation are not comparable at all. Last, in modern cranial opening studies there are no taphonomic actions that can alter the biological remains.

5.3 Scientific Rigor in the Criteria of Survival

Very recently, Buikstra and colleagues review the problem of the need for rigor in the palaeopathology of the twenty-first century in a paper entitled *'Scientific rigor in paleopathology'* [5]. They emphasise that palaeopathology is an interdisciplinary science that must consider all viable alternatives when establishing a categorical affirmation, avoiding preconceived positions. This must be rigorously applied when studying survival in primitive trepanations, including an arduous differential diagnosis. It is hard to explain the existence of skeletal signs of survival in more than a 75% of the cases studied in the Inca civilisation, when survival after surgical trepanations in the eighteenth century was only around 50%. Therefore, each of the cases of survival in the primitive trepanations should be demonstrated in a safe way, as well as reviewed and criticised when new study techniques appear.

The issue of survival is essential but poses many problems as it is sometimes too speculative, although there are clearly evident aspects. Hence, there is unanimity about the fact that it is impossible to differentiate a postmortem trepanation from another one carried out on an alive person but with very short survival time. The evidence of survival is based on proving the existence of signs of bone resorption and osseous regeneration on the margins of the remains. The bone resorption and repair stages are described from a pathological point of view and involve varying times of survival. However, as we have already mentioned, the main problem is that such pathological changes are difficult to be evidenced on the osseous remains by direct observation or even with the help of modern imaging techniques. In addition, even if they are found, it is impossible to accurately determine the influence of the taphonomic processes on the final state of these pieces. At the end, calculating the survival time is very difficult and subjective.

When the images from studies declaring a long survival are examined from a neurosurgical point of view it is often possible to find statements made by the researchers that are too conclusive. So, any osseous filling of the bottom of a cranial osseous hole, regardless of its size, is almost automatically understood as a sign of long survival, whereas, as we have mentioned, in modern neurosurgery it is uncommon to find this ossification after decompressive craniectomies or removal of bone splinters of any size, even after years of evolution. In fact, these ossifications of the depths of cranial defects are only observable from time to time in the case of trauma with comminuted or depressed fractures that have not been treated or in those fractures that have been surgically treated leaving enough bone matrix. Although the dura mater has osteogenic capacity, the lack of osteogenic stimulation due to the absence of compressive or distraction forces as stated by Wolff's law makes it highly unlikely to have a great osteogenic response. The problem is different in children, as it can be observed in the surgical treatment of craniosynostosis, in which the cranial openings that are surgically created usually become ossified early.

These considerations are not an obstacle to recognise that there are convincing data that evidence that a significant percentage of trepanned individuals survived a long time. The same happened with those individuals who suffered from depressed or fragmented cranial fractures secondary to severe direct traumas (normally during war interventions), whether they were trepanned or not. An explanation for the high survival rate is the aggregation of several favourable facts. Specifically, they were young individuals. Many of them were trepanned without intracranial injuries or with cranial trauma by direct impact, probably without internal secondary brain injuries. We must also consider the more than likely respect for the dura mater during the trepanation, as it was a clearly recognised membrane, with the probable lack of other associated diseases, with a good general condition of the people. Finally, the technique was well performed as it was exclusive of trained people who belonged to families or clans who had a good knowledge of such technique and were distinguished in their atmosphere and showed an interest in keeping that status.

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6 Historical and Geographical Areas of Primitive Trepanations

The map of findings of trepanned skulls includes many worldwide territories along the whole history of the mankind. However, they are particularly frequent in Europe and America. Trepanned skulls are also from all historical periods but their incidence was greater during the Neolithic in Europe and the pre-Columbian period in America. Thousands of prehistoric trepanned skulls have been documented. The incidence of trepanned skulls during the Neolithic is about 5–10% but it was even higher in pre-Columbian cultures.

A key element when it comes to drawing the geographical and chronological map of trepanations of primitive cultures was the funerary practices. It is impossible to find trepanned skulls within the many cultures that have left the corpses out in the open, exposed to animals, or that cremated them. In these cultures, due to the lack of any other written evidence, it is impossible to support or reject the statement that they carried out trepanations.

6.1 Neolithic Trepanations in Europe

It is considered that the European Neolithic period started about 5000 years BC. This period coincides in Europe with the emergence of agriculture. The European Neolithic almost ended after the introduction of bronze metallurgy (about 2000 years BC), when the incidence of trepanation drops probably due to the widespread of the cremation. During this wide period of time and during the beginning of Bronze Age, people carried out trepanations all around the European territories.

France is probably the country with the highest number of findings, which gathered in the department of Lozère and the area of Seine-Oise-Marne. There was a great interest in these type of findings at the end of the nineteenth century, during the first years after Paul Broca's initial proposals. This interest was particularly deep in the surgical field and, as a consequence, the issues arisen from the prehistoric trepanations were widely reviewed in the French treatises of that time on neurological and cranial surgery. Some examples include Leon Gallez (1864–1918) who addressed this issue in his book *'La trépanation du crâne'* from 1893, Antoine Chipault (1866–1920) who focused several pages of his book *'Chirurgie opératoire du système nerveux'* (which was published in 1894) on the *'Perforations crâniennes préhistoriques'* and F. Terrier and M. Péraire who did the same in their book *'L'opération du trépan'* which was published in 1895 or *'Les origines de la trépanation décompressive. Trépanation néolithique, trépanation pré-colombienne, trépanation des Kabyles, trépanation traditionnelle. Avec 32 figures'* by Just Lucas-Championnière (1843–1913) and published in 1912 [1–4].

A total amount of 100 cases of prehistoric trepanations have been documented in the Iberian

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Peninsula until year 2007. They were more frequent in coastal areas, particularly the Mediterranean coast, and have been gathered and thoroughly described by Domènec Campillo (1927–). They used different techniques but the cutting method can only be found on an exceptional basis. According to Campillo, the trepanations were carried out postmortem due to obvious ritual purposes. Whenever they were carried out on alive individuals, they were probably painful initiation techniques. They were seldom used when the patient suffered from a documented head trauma. Many trepanations were clearly carried out after the death of the individual. In Spain there is an important amount of trepanned remains and plenty of literature about this topic [5–7]. In the Mediterranean regions there are also prehistoric trepanations in Italy, with 36 documented cases until 2015. They used, just like the Iberian Peninsula, scrapping and drilling techniques. Cutting techniques were used on an exceptional basis as well. They were adult individuals who were trepanned on the frontal and parietal regions and frequently showed osseous signs suggesting survival. There are ten trepanned skulls that have been documented in Switzerland. They all belonged to young adults from both sexes and evidenced an estimated survival of 72% of the cases [8]. New findings of trepanations from Neolithic sites all around Europe and outside this continent are constantly being published [9–11].

There are also findings of trepanned skulls from more recent times. In the Swiss territory there are two documented cases from the Bronze Age and ten cases from the Iron Age. There are also findings from the Bronze Age in Greece [12]. Thirteen cases of trepanned skulls have been recently described in the South of Russia. They belonged to the Eneolithic period of the Bronze Age. A few cases of trepanned skulls from the Bronze Age have been found and studied in the Middle East (the current regions of Syria, Israel or Palestine) [13]. There are trepanned skulls that belong to the *'pazyryk'* culture from the Altai Mountains in Russia and from the sixth BC to second AC centuries [14]. Some trepanned skulls have also been found in Anatolia and India. A case of a Neolithic trepanned skull from the Dawenkou cultural period which was found in the Chinese region of Fujian has recently been published.

We would like to take some time to discuss the primitive trepanned skulls found outside the European continent as well, but not too far as these areas still belong to European nations. We are particularly alluding to the Canary Islands, close to the African coastline. The Guanche inhabitants of the islands arrived from the continent. However, no evidence of the existence of human remains previous to the year 540 ± 60 BC has been proved with C^{14}. The Spanish kingdom of Castile throughout the fifteenth century conquered the Canary Islands. The first trepanned skull was found in 1896. From a total amount of 1278 skulls located in the Canary Museum of Las Palmas, there are 23 with premortem trepanations and 3 with posthumous trepanations. Some trepanned skulls show cranial traumas and there is a high survival rate. The technique used was scrapping or boring, probably with basalt or obsidian stones with a cutting edge. We must remember that the Canary Islands are of volcanic nature. These rocks are locally called *'tabonas'* and were also used as weapons and household items. The location of the trepanations is mainly on the left parietal and the frontal bones and they have an elliptical or a circular shape. However, there is a single case of a triangular trepanation [15].

6.2 Trepanations in American Pre-Columbian Cultures

The number and frequency of trepanations in the pre-Columbian cultures vastly surpass those from the European Neolithic [16–21]. In this regard, we must consider several locations, concretely the Andean region, Mesoamerica and North America.

The first documented trepanation was a skull found in the south coast of Peru and dated from year 400. In the Andean regions of Peru and Bolivia there was a first trepanation period that corresponded to the pre-Inca times prior to the tenth century, when the Inca dominance started over these regions. The pre-Inca term means the cultural and historical reality of a specific territory before it was annexed by the Incas. Therefore, this term includes several cultures that spread over time and different geographical locations, such as Chavin, Paracas, Nazca, Mochica, Huari, Tihuanaco, Chimú and Huanca cultures. There is a great amount of cases that were excavated without guarantees from these areas and from the above-mentioned cultures at the end of the nineteenth century and the beginning of the twentieth century. However, the number of exhumed skulls is enormous. 15,000 Pre-Columbian skulls from the Andean high plains have been registered and among them more than 2000 skulls had been trepanned. About a 5–6% of the mummies found in Peru had been trepanned alive. Each culture had its own preference for a trepanning technique, which they used. As a curiosity, some of the findings might correspond to the first cranioplasties in the history. Hence, there was a skull with a frontal cranial defect on the middle line which was localised on the superior sagittal venous sinus and which was repaired with a nutshell. The evident signs of osseous regeneration confirmed that the individual survived and that the cranioplasty was carried out alive. Another skull found in Cerro Colorado (Paracas) shows a left frontal trepanation of a small size which was repaired with a gold sheet that widely covered the frontal region. The most probable indications for trepanations in these pre-Inca cultures were trauma and rituals [22].

Once the Inca expansion was complete, trepanations were carried out in the Inca Peruvian Empire (where the capital was Cusco) until the Spanish Colonisation in 1532 and probably sometime after, although there is no written evidence on the Spanish documents of that time. The incidence of trepanned skulls is incredibly high but it varies depending on the archaeological sites. So, there is a 17% of trepanned skulls among 341 cases in Urubamba and a 20% of trepanned skulls among 55 cases in Calca. 16.1% of the skulls studied from Cusco are trepanned. On the contrary, there are no trepanned skulls in the Machu Picchu city. It has been assumed that the reason was because people who came from this place belonged to the nobility. Andrushko and Verano thoroughly studied a set of 709 skulls from Cusco and its surroundings that were subsequent to the tenth century. Among them, 411 were in good conditions and belonged to individuals with more than 5 years of age. They showed that 16.1% of them had been trepanned. The techniques were pretty standardised in the Inca Peruvian Empire. All cases showed circular grooving and scrapping, excepting a single case that evidenced polygonal cutting. Between one and seven holes can be found per skull, with an average opening of 5.5 cm^2. The trepanations are localised on the parietal bone (72%), the frontal or occipital bones, on the left (27.5%), on the centre (60.6%) and on the right (12.7%), on sutures (44%) and on muscle insertion areas (only 11%). They were mainly carried out on young adults and teenagers, not on children, with a man/woman ratio of 1.84. There are evidences of an underlying pathology in many cases, specially skull trauma (44%) and, to a lesser extent, mastoiditis (3%). Osseous signs evidencing survival are very frequent as they reach an 83% of the cases, with only 4.5% of osseous infections after the trepanation [23].

Pre-Columbian trepanned skulls have also been exhumed in Central America, particularly in Yucatán and Monte Albán (in the Oaxaca Valley, Mexico). Around 25 cases corresponding to the so-called Classical Period between years 250 and 800 have been found. Most part of the trepanations were carried out by scrapping and boring but there are seven trepanned skulls with holes of about 11 mm of diameter that were made with a reed or bone and abrasive sand. The skulls usually show multiple trepanations, up to five in one case. The postulated indications include rituals, headache and headache associated to the use of bandages for cranial remodelling [24, 25].

Finally, some trepanned skulls were also found in North America. Nineteen trepanned skulls had been described until 1990, 11 of them in Canada and 8 in the United States. They all belonged to the pre-Columbian period and were trepanned by scrapping on the parietal region (nine cases), frontal region (three cases) and occipital region (three cases). One of the skulls shows two trepanations and the average extension of the opening is 3 cm^2. There are no cases showing fractures and the osseous signs of survival are pretty common, as they appear in 90% of the cases [26].

6.3 Trepanations in Contemporary Primitive Cultures

There is documentary and even iconographic information on trepanations that were performed in very recent times within primitive cultures from the Caucasus, Berber cultures from the North of Africa, some Polynesian islands and black tribes from Central Africa. What is particularly interesting from these trepanations is the fact that there is direct information about the technique, instruments and justification as there are independent and reliable witnesses that have documented them.

There are direct descriptions published in 1888 by I. Krivyakin, a Russian army doctor, about trepanations carried out in the Dagestan Mountains (Caucasus) with a chisel. He pointed out that they were made to alleviate headaches and trauma, although they were often made just to earn money. Patients were calmed and seemed not to suffer during the intervention. A. Chipault observed at the beginning of the twentieth century that, 50 years before, that is, towards the mid-nineteenth century, the indigenous inhabitants of Tahiti used to lift the fragments of comminuted fractures with a shark tooth and covered the defect with a concave piece of pierced pumpkin rind that was tied to the head. He also related that, 20 years before, the native people of the Society Islands carried out trepanations with a piece of volcanic glass and that they protected the loss of osseous substance with a smoothened piece of coconut shell, onto which they relocated the skin flap. Some trepanations that were carried out by primitive peoples from the territories of New Ireland and New Britain in the Pacific, Ogaden in the Horn of Africa and the Zagros Mountains in Iran have also been documented in an anecdotal way.

More frequent observations have been made in North Africa [1–4]. Another army doctor, in this case the French physician Amédée Paris, described on a paper of barely 20 pages (*'Mémoire sur la trépanation céphalique pratichée par les médecins indigènes de l'Aouress'*) the trepanation carried out by the Berber people from the North of Africa. He was a direct witness thereof during the years 1859–1861 [27]. The trepanation aimed to lift a square cranial plaque of bone. According to the author, who had the chance to study many survivors, the indications for the trepanation included simple and comminuted fractures of the skull, cranial lesions of any kind (*'l'os est carié ou necrôsé'*) and necessity to treat headaches in individuals of all ages. The author described a trepanation carried out on a person after a fight. The trepanned patient aimed to take advantage in the next pending dispute, arguing that he had been trepanned due to a cranial fracture. The instruments were metallic and had a wooden handle. The author reconstructed them based on the original ones, as the owners thereof considered they were sacred and did not donate them. The trepanning technique included shaving the head on the area where the trepanation was going to be carried out, normally the right parietal region. Afterwards a square cut was made on the pericranium with a knife, reaching the bone. This way, a square of soft tissue was removed to expose all the surface of the bone that was going to be removed. The bone was cut directly by longitudinal incisions that cross formed a right angle by means of a simple or double-cut metal saw. A square piece of bone was lifted with straight or curved bone lifters whenever it was possible, i.e. when the internal table had been weakened enough. Once the skin square and the underlying fragment of the skull (also square) had been removed, the empty space was filled with cotton and wool pieces and a slightly concave, circular, copper plate of about 5 cm of diameter was applied onto the wound. The plate had multiple holes through which wool clamps went. They allowed to firmly apply the plate onto the wound and secure it to the head. The wound healed by the secondary intention method during weeks or months. The copper plate, the bandages and the ropes were changed and replaced until the wound finally healed. Paris had the chance to assess in person five survivors. In two cases the osseous defect was covered by a whitish scar which was tough and depressed in the centre, whereas the other three showed granulation tissue that allowed to recognise the cerebral movements by palpating it.

The book written in 1895 by Terrier and Péraire, entitled *'L'opération du trépan'*, includes more interesting details through the descriptions of A. Védrène, particularly concerning those people in charge or carrying out the trepanations (called *'thébibs'*). They had often been trepanned once or more times and were accompanied by their wives, who sometimes cared for the trepanned and were in charge of changing the dressings. They even identified two different schools, one in Teberdéjà and another one in Chebla, where the *'thébibs'* or trepanners from other regions went to learn the job. Chipault provides more accurate information about a family of *'thébibs'* (the Ouled-Miras) from the Mountains of Aurès, located 100 km to the south of the Algerian town of Constantine. They said that they had treated the native people of the region over centuries and their tradition, which passed down from one generation to the next, was written on a manuscript. Each trepanner had a copy of the manuscript, which contained the indications for the trepanations and the technical specifications of each trepanation. This supposed manuscript could not be seen or consulted by European witnesses.

These trepanations carried out in the North of Africa have been documented more recently by Hilton-Simpson between the years 1913 and 1922 in the *'shawiya'* Berber tribes from the Mountains of Aurès in Algeria. He was allowed to study the surgical instruments used. They were still indicated for skull trauma, preferably in the first week. They basically used the above-mentioned technique, which includes the circular grooving of the soft tissues, cutting the bone with a saw and placing a temporary external protection made of leather or metal that was secured to the head of the individual with ropes.

There are some general rules in the technique of trepanation done in North Africa. At no time were the dura or cranial sutures (the fingerprints of Allah) violated, and the variety and workmanship of the instruments used were quite excellent. Holes were made in the skull with a hand-twirled drill and connected by means of a serrated saw. After the holes were drilled, any blood or pus under the bone was drained and any pathologic bone removed. A dressing was then applied that consisted of sheep's butter, pine, resin, honey, and wheat flour. No sutures were even used, and the dressing was removed in 2 weeks. An interesting variant of this procedure was a staged technique wherein all the incisions and bone work were done in one step but the bone was then removed 3–15 days after. The medicine men in these areas claimed excellent pain relief, and the restoration of consciousness following injury. It seems that the amalgamation of Neolithic and Arabic practices produced a hypothetical line of evolution for the history of North African trepanation.

The second area of Africa where cranial trepanation has been practised until very recently is eastern central Africa [28–30]. It is astonishing that there are even descriptions of direct observations of primitive trepanations, particularly Kenya and Tanzania under British and German colonisation, respectively. Hence, the *'kisii'* tribe from Kenya occasionally carries out cranial trepanations that are characteristic of primitive cultures, although they use modern surgical instruments, not only to cut and close soft tissues but also to drill the skull. The shaman or medicine man of the tribe gives the indications for the trepanation and carries it out. Just like in all-ethnic groups from Kenya, the medicine man or *'ubanyamorigo'* has a very privileged status within the tribe. One of the practices still consists of resecting part of the spine or the skull in those cases when the patients suffer from backaches or brain disorders, respectively. A journalist documented with photographs one of these interventions. Although it was not published until 1994, the report was made in 1977 and the pictures were taken by Michael D. Mueller, who was a member of the 'Explorers Club' of New York. The intervention was carried out by the *'omobari omotwe'* (head surgeon) and the photographic report sequentially shows the whole surgery and the patient's general condition during the post-operative period. It is possible to find reliable, iconographic and sequential documentation on the Internet that has been gathered using a series of photographs. This lets us know in detail the *'kisii'* trepanation technique, which we will later describe in detail by an illustrative case.

Other interventions of this kind that were carried out by the '*kisii*' can also be consulted and seen in YouTube under the entry 'trepanation kisii'. One of them shows a trepanation using a different technique. In this case no local anaesthesia is applied and they employ their own and traditional instruments. They make a linear cut and remove fragments from the skull that are cut by sewing movements with a cutting instrument. After washing the wound with water and applying traditional ointments, they close it by approaching the margins with strips made of leaves from banana trees. The strips are passed under the chin and tied firmly. The intervention takes several hours. The film shows several survivors who underwent this trepanation. They have scars with large dehiscence and white, fibrous cicatricial tissue. They are wearing hats to protect themselves from the sunlight. The narrator relates that the survival rate is 96%, that it is used to treat any pathology or headache and that one person had been trepanned up to 15 times. Finally, there is also a shocking German documentary about cranial trepanation entitled *'Safari in die Steinzeit. Die Schädelöffner der Kisii in Kenia'*. It includes several cranial surgeries carried out in the *'kisii'* tribes as well.

6.4 Illustrative Cases

The lack of written evidences concerning the trepanned skulls in ancient primitive cultures is clearly an obstacle to describe and analyse them. For this reason, we have chosen two cases with some available documentary information that correspond to one of the trepanations carried out in the North of Africa during the nineteenth century that was recorded by Védrène [4] and the *'kisii'* trepanation of which Mueller took photographs by the middle of the last century [29].

6.4.1 Trepanation in the North of Africa

Védrène, who was an army doctor in Algeria, reported that on the 10th of April of 1869 a 10-year-old boy who had accidentally fallen from the balcony of his house onto a pile of stones was referred to him. The boy had undergone a trepanation 40 days before. It was done to treat a supposed skull fracture. The characteristics of the trepanation were those typically attributed to the trepanations carried out by a *'thebib'* according to the previously described technique. When examining the wound, the square edges of the trepanation could be observed. It was mainly occupied by outgrowths of granulation tissue, through which the beats and the movements of the brain could be noticed. The reason for consultation was that the family of the child claimed against the French jurisdiction that they did not want to pay the trepanner's fees as the trepanation had been done without any apparent reason and the intervention was incorrectly done. There were no more information or data about the clinical situation of the child during his evolution after the trauma. He apparently was in good condition when he was examined by Védrène.

The expected injury on a child with an already synostosed skull who has fallen from heights and has had a direct impact on his skull with stones is a comminuted depressed fracture normally associated to a wound in the pericranium. A common complication is the epidural haematoma secondary to the fracture itself or to the break of any meningeal vessel. Nowadays, most of the open comminuted depressed fractures are surgically explored to be cleaned, to lift bone fragments, to remove non-viable bone fragments or foreign bodies and to repair the dura mater if it has been injured. Computed axial tomography can identify a possible epidural haematoma and its size, along with other brain injuries that might deserve surgical treatment. Hence, the surgical indication might have existed as well in a modern neurosurgical environment. However, the current technique does not resemble at all the one used by the *'thebibs'* in the illustrated case. The skin is not removed. Instead the neurosurgeon takes advantage of the wound to make a pericranial flap with a good blood supply that can be closed without tension after removing the non-viable or bruised parts. In case there are big cranial fragments, these will be lifted after removing foreign bodies and small bone fragments. The epidural blood is evacuated and the dura mater is examined. It will be repaired in case it has been broken. If there are no underlying intradural injuries that require examination or treatment the dura mater will not be opened. The *'thebibs'* did not observe this consideration at all. The dura mater is lifted by means of some hanging points that are fixed to the bone edges to prevent blood from accumulating during the post-operative period. As a general rule, bone fragments are secured to the edges of the skull or are replaced to maintain the brain protection using different cranial fixation systems. If, for whatever reason, a cranial decompression must be carried out, the skull reconstruction by cranioplasty techniques will be done after some time. The skin is always closed, trying to avoid the tension on the suture line.

6.4.2 'Kisii' Trepanation in Kenya

We now describe the case that was photographed by Mueller in 1977. It consisted of a trepanation intervention carried out by the *'omobari omotwe'* (head surgeon) in a *'kisii'* small village in Kenya. The patient was a young woman with a 5-year history of headache and dizziness after falling and suffering from a cranial trauma. Mueller says that the patient was moving slowly and showed no emotions when she arrived at the place of the trepanation. The intervention started early in the day, when the body and the blood are fresher. This reduces the possibility of bleeding. It was done outdoors with the patient sitting on the ground and a relative holding her head. The head was shaved and a local anaesthetic was injected into the pericranium. The trepanner made a cross-shaped cut reaching the bone. The cut was localised on the area of the skull where the patient felt the pain. The bone was widely exposed by retracting the pericranium with galea hooks and manual retractors. The medicine man took the saw and violently sawed the skull for about 10 min. Once the intervention was over, different ointments and a dose of penicillin were applied onto the wound. Finally, the head was bandaged with a piece of cloth and the patient stood up accompanied by her relatives. The post-operative care recommendations included eating beans with no salt, tea with no sugar and avoiding milk as well as barks or people cutting firewood around her. As it has been mentioned, the surgical instruments are both modern (such as syringes or haemostatic forceps) and traditional (such as retractors, saw and some kind of chisel). There is neither more clinical information prior to the trepanation nor the late clinical result thereof.

A clinical presentation with headache, dizziness, bradypsychia and emotional response disorder 5 years after a cranial trauma can be the consequence of what we nowadays know as post-traumatic diffuse axonal injury. It is due to multiple small lesions on the cerebral white matter with a secondary functional disorder with variable intensity and duration depending on the seriousness of the injuries. Diffuse axonal injury has no surgical treatment. An alternative hypothesis would be a post-traumatic meningitis and that the clinical manifestations of the patient would be the consequence thereof or due to a secondary hydrocephalus. Nowadays these injuries are not treated with a craniotomy either. The hydrocephalus requires a surgical cerebrospinal fluid shunting. Another possibility would be that the patient's symptoms were not due to the trauma, from neuropsychological or psychiatric disorders to a long list of chronic degenerative. In this case there is a wide range of options, infectious or inflammatory neurological diseases. The technical aspects and the differences with current craniotomies are also important. Many of them are similar to the ones commented in the previous illustrative case report. The use of local anaesthetics is a remarkable aspect that must be highlighted. In modern neurosurgery craniotomies and complex neurosurgical interventions are carried out on awake patients. A local anaesthetic is applied into the pericranium in those cases with lesions in motor or speech areas that require active collaboration from the patient during surgery. Patients tolerate well these type of interventions thanks to a previous explanation of the procedure and a light pharmacological sedation.

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Part III

Origins. Trepanation in Classical Mediterranean Cultures

(terebra) one like that used by smiths, the other longer in the blade, which begins in a sharp point, suddenly becomes larger, and again towards the other end becomes even smaller than just above the point
(modiolus) a hollow cylindrical iron instrument with its lower edges serrated; in the middle of which is fixed a pin which is itself surrounded by an inner disc

Walter George Spencer (1858–1940)

7 The First Documented Reports of the Surgical Trepanations Appear in the Corpus Hippocraticum: Greco-Roman Trepanations

The osteoplastic craniotomy, which was invented at the end of the nineteenth century, is the surgical procedure that defines modern neurosurgery and is characteristic thereof. If we retrospectively track the cranial opening techniques starting from such osteoplastic craniotomy, we will go back to the Hippocratic texts dated from 400 BC with no continuity solution. These texts describe cranial trepanation and are consequently considered as the first documentary source of medical and scientific knowledge on this issue. The practice of cranial openings or trepanations in a great number of primitive cultures that were spread worldwide and throughout history is a separate matter, which has been thoroughly analysed in the previous chapters.

In this section we analyse the vicissitudes of the surgical cranial opening from its origins, actually from the first documented description of the trepanation technique and indications, and we also review the instruments and the technical aspects used for this purpose by the classical Mediterranean civilisations.

We will use again the term trepanation with the same meaning as in the previous chapters, i.e. the technical action and the consequence of trepanning, with no connotation on the size, techniques or aims or goals that led to such action. However, we must take into consideration some differential features when compared with the primitive trepanations. In the historical period that we are now studying, wide cranial openings were less frequent and sophisticated than those performed by the primitive cultures. Most significant, the technique and the instruments were also different, as well as the fundamentals of the trepanation. In this period, cranial openings were normally small and were performed by drilling with metal instruments designed for such purpose, such as the *'terebra'* and the *'modiolus'*. Large cranial openings were occasionally performed due to the treatment requirements. In those cases, the opening started with one or several drills that were enlarged or joined together by means of a chisel and a mallet. Large cranial openings could also result from removing fractured osseous fragments or performing clumsy resections with the chisel and the mallet. These types of enlarged cranial resections will be generically called also trepanations. However, the most important difference between primitive trepanations and the ones we are currently studying is that the latter trepanations are actually surgical procedures. That is, they had a therapeutic or diagnostic purpose and were carried out by surgeons and not by shamans.

Historically speaking, in this chapter we cover the chronological period between the ancient Greece and the beginning of the European Middle Age, that is, the so spectacular and sophisticated Greco-Roman civilisation.

As we will show, the trepanation technique as a surgical treatment option had its first documentary sources in Greece. These primeval elements,

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along with other cultural, social, legal, political, scientific and knowledge-related aspects, were born and spread from Greece to the whole Mediterranean region and subsequently to mainland Europe, creating thus the essential core of our cultural heritage. In contrast with the primitive cultures studied in the previous chapter, we now include cultures in which there has always been any type of written material from which the historiographical information has been obtained. Unfortunately, most of this original documentation has been lost and only copies and translations are available. Therefore, the human remains and the archaeological evidences are less significant. Contrary to the primitive cultures, in which there are no evidences of information exchange among them, in this case cultural exchanges were deep, and it is possible to track such exchange, which also acts as common thread among all of them [1].

In geographical terms, all these cultures developed around the Mediterranean basin, more specifically in Egypt, Greece, Rome and Byzantine Empire and later in mainland Europe, the Middle East and the North of Africa. In the particular case of trepanations, everything starts with an essential bibliographic reference that allows their study, namely the works that make up the '*Corpus Hippocraticum*'.

7.1 Trepanations in Ancient Mediterranean Cultures: Ancient Egypt

Although this part of the history of cranial opening was born in Greece, we will also stop for a while to review the trepanations performed in other ancient Mediterranean civilisations due to geographical and contextual proximity, especially Ancient Egypt [2]. Throughout the history of Ancient Egypt, before the Greek and subsequently Roman influence, there are no descriptions about the techniques, indications or instruments related to cranial trepanation. No trepanned human skulls have been found either. So far only three written documents on medical issues have been found: the so-called Ebers, Hearst and Edwin Smith papyri, named after their first owners. In all these documents medicine is based on magical beliefs and superstitions.

The Edwin Smith papyrus (700 BC) contains plenty of narrations related to surgical practices. Although penetrating injuries in the skull are mentioned, the treatment thereof is poorly described and there are no references to trepanning. There is no information on this concern in the other two medical papyri either. Sir Grafton Elliot Smith (1871–1937), an Australian-British neurobiologist and Egyptologist, did not find any evidence of trepanning in about 15,000 ancient Egyptian skulls studied at the beginning of the nineteenth century, showing thus that trepanning was a scarce or absent practice in Ancient Egypt. Only some exceptional cases have been exhumed, but they correspond to the late Ptolemaic and Roman periods.

However, the public opinion perceives that cranial trepanation was a common practice in Ancient Egypt. This mistaken belief is due to the enormous success and the media coverage of the novel *'Sinuhé egyptiläinen'*, from the Finnish writer Mika Waltari (1908–1979). The novel, which was published in 1945 in Finnish, became a worldwide best seller in the English version 'Sinuhe the Egyptian', being translated to a lot of languages including the Spanish [3]. In the book the author describes the life of Sinuhe, a physician from the royal court that performs numerous trepanations, some of them due to trauma, some with the aim of treating a concrete pathology and others without an explained cause. The text highlights the importance of cleanliness, asepsis and use of narcotics and describes the use of surgical instruments similar to the Greek ones which were introduced only centuries after. The story takes place in Ancient Egypt, approximately during the reign of Amenhotep IV (1353–1336 BC), who changed his name to Akhenaton and started worshipping a sole sun god called Aton. This means that the story takes place many centuries before the Ptolemaic era, the only period in which some trepanations have been proved to exist in Egypt.

Actually, Waltari's Sinuhe is a fictitious character, although his life and his social, cultural and professional context are based on different historical accounts that were subjected to the free and idealising interpretation of the writer. *'The Story of Sinuhe'* is indeed one of the most famous accounts of Ancient Egypt and contains the trips, adventures and misfortunes of an important nobleman from the court of the pharaoh Amenemhat I, who was murdered around 1962 BC. This triggers Sinuhe's self-imposed exile and flight during decades until he is rehabilitated and can return under the protection of pharaoh Sesostris I and dies in peace in Egypt, as he wished. As we have mentioned, the authentic Sinuhe was a nobleman and an adventurer, a warrior and a tribal chief in the desert until he returned to Egypt, but he was never a physician [4]. Sinuhe's adventures are gathered with the same events and in a more or less comprehensive way in many authentic papyri and ostracons (stone layers). This shows the success of the story in that ancient time, regardless of the veracity of the facts narrated.

Waltari's novel contains information about seven trepanations performed by the fictional Sinuhe, although he only acted as an assistant in the three first ones. We are going to briefly describe them along with the modern diagnosis deduced from the literary text. The first one is a training intervention performed on an old slave who dies during the surgery. The surgery was immediately followed by another one, a case of a young slave with an epidural haematoma. The third one is a trepanation carried out on the pharaoh just before his death. As according to the novel, the pharaoh had to be trepanned before his last minutes if he did not die a natural death. Sinuhe personally carried out the rest of trepanations on a nobleman with a meningioma, for mercy on a dying man, on a patient with post-traumatic epilepsy in which they came across a chronic subdural haematoma that is evacuated although the patient dies, and on a patient with an acute phase of a traumatic brain injury. Eventually, Akhenaton appoints Sinuhe 'royal trepanner'. For this reason, he accompanies the pharaoh during his military campaigns, in which he performs many trepanations, such as those carried out on the soldiers whose skulls were dented due to the Hittite maces. In the novel, the pharaoh Akhenaton repeatedly requests Sinuhe a trepanation on himself to treat certain psychological disorders. Sinuhe always refuses to do it, even just before his death.

As in the case of Ancient Egypt, there are so far no findings or references of cranial trepanations in other ancient civilisations from the Mesopotamian area, such as the Assyrians, Babylonians or Sumerians.

7.2 Trepanations in Classical Greco-Roman Mediterranean Cultures

As we have mentioned, we can affirm that all the knowledge related to osseous and cranial trepanations until the Renaissance is based on the guidelines on this concern included in the so-called *Corpus Hippocraticum* and that were presumably provided by Hippocrates of Kos (460–337 BC). Until then no other medical or literary text on medicine or medical/surgical treatments contained any direct or indirect reference to cranial trepanations, although some references or commentaries related to cranial injuries or traumas and their handling could appear.

The *'Corpus Hippocraticum'* contains about 50 works but the originals are not preserved [5, 6]. In fact, Soranus of Ephesus wrote the first biography of Hippocrates about 500 years after his death. It seems that the first texts were kept on the island of Kos between the years 420 and 350 BC and other anonymous texts were added subsequently in the Library of Alexandria. The different vicissitudes of history, especially the collapse of the Byzantine Empire, caused the originals and the first copies to disappear. This forces us to retrospectively track this spectacular work by means of translations and subsequent handwritten copies. The first print edition in Latin was published in Rome in 1525. It was subsequently published in Greek in Venice in 1526, guaranteeing thus a wider dissemination thereof. Pedro Laín-Entralgo (1908–2001) carried out a study in which he classifies the Hippocratic texts in different groups according to the probability that *'fueran escritos por el propio Hipócrates con toda seguridad, con cierta seguridad, por autores contemporáneos de la escuela de Cos o, finalmente, que no pertenezcan a Hipócrates ni a su escuela'* (They were surely written by Hippocrates himself, probably written by Hippocrates himself, by contemporary authors from the School of Kos or, finally, those that do not belong to either Hippocrates or his school) [7]. We have consulted a classical version translated of the *'Corpus Hippocraticum'* into English in 1868 by Charles Darwin Adams for this study [8]. Many other old translations of this seminal book are available in different languages done along history. As an example, we have read for this study the translation to old Spanish by J. Montemayor done in 1651 [9]. Some recent works address this issue from a neurosurgical point of view, highlighting those aspects related to the treatment of head injuries, skull fractures and trepanation [10, 11].

Among all the texts that make up the *'Corpus Hippocraticum'*, we are especially interested in the book titled *'On Wounds of the Head'* (Gr. *'περὶ τῶν ἐνκεφαλῇ τρωμ άτων'*; Lat. *'De capitis vulneribus'),* which according to the classification made by Laín-Entralgo would have probably been written by Hippocrates himself. The book addresses the issue of traumatic head injuries and their treatment, along with a description of the anatomy, symptoms, evolution, complications and treatment indications for head injuries. It is therefore a comprehensive medical, clinical and therapeutic approach of the problem, considering the spirit and limited knowledge of that time. However, it marks the beginning of scientific or technical medicine, which according to Laín-Entralgo consists of the fact that the physician does something rationally knowing what they are doing and why. This action is related to the knowledge of the illness and its cure. The text describes the types of osseous injuries in the skull: bone bruises or contusions without fracture; with linear fracture; depressed fractures; cranial perforation with indentation; dinted fractures or *'hydra'*; and, finally, skip lesions or distant lesions from the scalp wound. The text describes also the types of treatment, including the examination and dressing of the wounds, the removal of the bone fragments and trepanning. As we will see later, the text stresses the importance of avoiding the trepanation in depressed fractures and on sutures, as well as avoiding damaging the dura mater, suggesting even keeping unhurt the internal table. On the contrary, the description of the surgical instruments is regrettably not very detailed, although both the *'terebra'* and *'modiolus'* are explained.

It is important to specify the types of fractures described, as there is much confusion about the correspondence between the explained injuries and the way we currently classify skull fractures. The first type can be described as a bruising or contusion of the bone with a fissure fracture, which would correspond with the modern linear fractures. Several variations of these fractures are defined in the text, according to the size, length and separation of the edges or the degree of affectation (partial or total) of bone thickness. The second type is the contusion or bruising of the bone without fracture, which is a suspected injury in a case of direct trauma to the bone without evidencing any fracture when examining the wound. The bone would result, in any case, focally depressed. The third type would be the depressed fracture of the skull, which might have different degrees according to the size of the fractured bone and how dented the fragments are. The fourth type would be a fracture with bone indentation, which is described in the text as a hydra ('εδρα'), which is the simple impression caused by the traumatic instrument. In this case we presume a bruising of the bone, causing it to dent. Sometimes it can be accompanied by a fracture. We can consider that these types of fractures have different degrees of severity. The lowest one would be the mere depression of the bone caused by the impact, which are currently named 'ping-pong fractures' and are almost exclusive of children due to the elasticity of the bone, which deforms before breaking. A higher degree would be the fracture of the outer table of the skull. The strokes thereof would have a radiated aspect from the point of impact, resembling the head of the hydra. A greater degree would be indistinguishable from a depressed fracture. Finally, the fifth type of fracture consists of skip fractures that are originated distant from the point of impact or the injury or, following the modern name, 'contre-coup fractures'. We must highlight that in the text any type of fracture involving any cranial suture poses additional severity.

It does not seem unreasonable to assume that the knowledge gathered in the authentic original version of the Hippocratic book *'On Wounds of the Head'*, whoever wrote it, was neither just the final product of the personal work of either its author nor even probably the fruit of the School of Kos, to which its creator belonged. Just reading the text makes us suppose that it was nearly impossible that the author of the text created out of nothing all the remarks on a detailed and methodical description of the indications and the technique of trepanning.

The problem is that there are no previous texts or remains that let us reconstruct this period before the fourth century BC. Some archaeological data in Greece prove that trepanations were carried out before Hippocrates and the School of Kos, during the Bronze Age, although the number of findings is scarce. Mountrakis and collaborators have recently reviewed these findings and provided a case of trepanation carried out by means of the scraping technique [12]. Papagrigorakis and collaborators have also provided a new case more recently [13]. All the cases included in these studies correspond with trepanations similar to those described for primitive cultures, in which cranial perforation is not performed with any surgical instrument specifically designed for that purpose.

However, Fornaciari described and studied a very particular cranium just recently. It is a skull with a perfect circular trepanation performed on the frontal area [14]. The hole is what you really would expect to have been made by a *'modiolus'*, as it was described in the *'Corpus Hippocraticum'*. The dating of the tomb reveals that the skull is very likely to belong to a period between years 525 and 480 BC, that is, before the birth of Hippocrates, dated from the year 460 BC. This would prove that the *'modiolus'* described in the Hippocratic book *'On Wounds of the Head'* had been invented and used before the first texts of the *'Corpus Hippocraticum'* were written and, consequently, that those surgical instruments existed in Greece at least from the fifth century BC.

Leaving the cranial trepanation aside, it is obvious that Greek medicine must have suffered a conceptual revolution that let it abandon the magical or empirical conception that was characteristic of the medicine within primitive societies. Therefore, it was from the sixth century on when the figure of the physician or healer appeared in Greece as a rational scientific professional who is embodied (probably in such a magnified way) in the author(s) of the *'Corpus Hippocraticum'* and, consequently, in the figure of Hippocrates of Kos himself. The question is to know what type of medicine existed before this remarkable conceptual change, and when this change happened.

The documental sources from the Homeric Age (eighth century BC) are basically the *'Iliad'* and the *'Odyssey'*, in which there are descriptions of war wounds that sometimes are very precise and full of anatomical details. That anatomical knowledge could only have been acquired by direct observation, war wounds and analysing corpses not worthy of cremation, which were abandoned to decomposition. However, medical knowledge was still on a magical and empirical nature characteristic of primitive cultures. This is why the change of paradigm discussed took place later, during the seventeenth century BC. Laín-Entralgo concludes that, due to the lack of any other information, this transformation was carried out as a consequence of a philosophical and ideological evolution of the healers of that time [7]. Such a change of mentality must have included at least the following aspects: adopting a position with no dogmatism, being open-minded, accepting that the magical action of the procedures has limits imposed by the reality of the body or the environment and others. These changes of mentality arose in that time within certain medical schools in Crotone, Cnidus and Kos, which ended up imposing this shift towards a technical or scientific medicine as it was reflected in the *'Corpus Hippocraticum'*.

We can find an important link in this history of trepanation chain in Rome centuries after. Cornelius Celsus (25 BC–50 AC) was a Roman encyclopaedist, and maybe also a physician although there are no true evidences of this. He was probably born in the Gallia Narbonensis (France). His only work that has survived to the present day is *'De Medicina'*, but the original version thereof is not preserved either and was printed for the first time in Florence in 1487. We have consulted a classical version translated into English in 1935 by W.G. Spencer [15]. Osseous and cranial trepanation is described in detail as well as the instruments used to perform it in the last of the eight books. Celsus is far more explicit when it comes to describing the instruments and their use than Hippocrates. Celsus' work is considered to be the most important one of ancient times after Hippocrates' writings. However, as it was lost during centuries it was neither transcribed nor translated by the Muslims. Celsus' original work was recovered after being found in 1443 by the subsequently appointed Pope Nicholas V. This way it returned to the medical heritage of the Renaissance. Moreover, it was the first printed Greco-Roman medical work, even before Hippocrates or Galen's writings. This conferred it a great superiority from that moment and during centuries among physicians.

Other authors added contributions to the technique or indications of trepanation, although they were minor. Among them we must highlight Archigenes of Apamea (c.75-129), who was born in Apamea (Syria) and described the post-traumatic intracranial accumulations and effusions, pointing out that in skull fractures blood can accumulate between the dura mater and the bone. This can be observed as it is transparent, just like under the nails. Blood can turn into pus over time and it changes then the aspect of the bone. These fluids can be easily evacuated by drilling the skull.

One of the most renowned physicians of ancient times is Galen of Pergamum (129–210), who also addressed the trepanation issue for head injuries. Galen was born in Pergamum (Asia Minor) and after numerous trips he moved to Rome in the year 163, witnessing the ruling times of two of the greatest Roman Emperors such as Antoninus Pius and Marcus Aurelius [11, 16]. He was the physician of the gladiators. This is why it is assumed that he had to assist countless traumatic injuries. He wrote more than 500 works in Greek. Many of them were lost due to different vicissitudes, which made him rewrite them. Galen made important contributions to the anatomy of the central nervous system and to clinical neurology. However, these innovations contained many mistakes. In spite of that, Byzantine physicians considered Galen as the only and true ancient physician. His ideas turned into a dogma and were kept unchanged through medieval Islamic and European copies and translations of his works for more than 1500 years until they were finally criticised and reviewed in the European Renaissance. Among his works we can find *'Head Injuries',* in which he follows Hippocrates' footsteps and refers to cranial trepanation. The indications include haematomas, depressed fractures and inflammation but he is particularly restrictive when suggesting trepanning. As for the technical aspects, he insists on the need of keeping the dura mater intact and reducing thus the blood loss. He places great value on anatomy, repetition, experimentation and practising with animal heads, such as monkeys or bovine cattle. He made public and private demonstrations of vivisections in animals, exposing the brain [17]. As for the instruments he introduced new elements in the armamentarium, although he kept on using the '*modiolus'* or crown trepan that makes orifices or holes and the *'terebra'* or piercing trepan which is used to achieve a circumferential or perimetric trepanation surrounding the injury removing a bigger piece of bone by making multiple small holes around it. He also used the '*meningophylax'* or guard of the membranes, like the dura mater. Galen's greatest contribution to surgical instruments is the so-called *'abaptista'*, a driller that has a drilling stop supposedly as a flange over the cutting edge to avoid injuring the dura mater. However, in practice Galen recommended performing the trepanations with the chisel and the mallet, as he was reluctant to use drillers and, in general terms, to carry out trepanations. The safest and quickest way of performing a cranial trepanation would be by means of a particular knife named *'lenticular',* which is described in a detailed way.

This medical and technical knowledge persists without significant contributions throughout the entire time of the Roman Empire. Much later, in the seventh century, we must consider the works of Paulus Aegineta (625–690?), who was a Greek Byzantine physician born in the island of Aegina and who was living in Alexandria by the time it was conquered by the Muslims. He compiled texts from the Latin and Greek Schools. His complete original work was published in Greek in Venice in 1528 and later in Basel in 1538. His works were translated into English by the Scottish physician Francis Adams in the nineteenth century and were titled *'The Seven Books of Paulus Aegineta'* [18]. We have consulted this text, which expressly refers to fractures of the head bones and describes the indications, techniques and instruments related to trepanation in section XC of book VI, which focuses on surgery. Paulus Aegineta's books were copied, translated and followed for centuries in Europe.

As we have mentioned, almost all aspects related to medicine and the medical and surgical treatment of diseases were originally based on the doctrines included in the *'Corpus Hippocraticum'* for centuries. Generally speaking, it is the same with cranial trepanation. The first impression we have when reading the book *'On Wounds of the Head'* is that it addresses almost all aspects of diseases which concern us nowadays, excepting from physiopathology. This is due to the fact that the *'Corpus Hippocraticum'* actually represents the beginning of medicine as a technical knowledge (Lat. *'ars medica'*, Gr. 'τεχνη ιατρικη', *'tekne iatriké'*). The book *'On Wounds of the Head'* successively reviews the anatomy of the skull, the types of traumatic injuries of the skull, how they are produced, the clinical aspects on prognosis, the environmental factors that influence the prognosis, the anamnesis, general treatment of the trauma patient, the treatment of injuries and the surgical and nonsurgical treatment of fractures regarding their type, the evolution times and the patient's condition. As for cranial trepanation, the book describes in detail the indications and contraindications thereof, along with the trepanning locations, technique, prevention of complication guidelines and instruments needed and how to use them. This same impression is obtained when reading Celsus' *'De Medicina'*, in which the technical accuracy of the descriptions and the instrument usages is even greater. However, this exciting first impression should be corrected as we must consider that we have actually read a modern translation into English of previous texts, which are in turn the result of successive translations, copies or re-editions throughout more than 2000 years during which a great number of corrections and new knowledge have been added along with mistakes.

In spite of the importance and significance of the contributions made by the Greco-Roman authors, the number of trepanned skulls of this period that has been found is scarce, although there are descriptions throughout the whole Greek geographical area, as well as in the Roman Empire. One of the reasons given was the widespread practice of cremation of corpses, both in Greece and in Rome. This reduces the probability of finding trepanned human remains of that time. Mariani-Constantini indicates that until 1999 only three cases of cranial trepanation have been found in Italy dating to the Roman culture, namely from the Imperial period [19].

Cranial trepanations performed with the *'modiolus'* are easily recognised due to their perfectly circular shape. The opening has the same diameter both in the outer table and in the internal table; this is why its edges are vertical. Brothwell describes a case in which a trepanation carried out with a *'modiolus'* is evident on the left temporal region of a skull that was exhumed from a Roman cemetery in York (UK) [20]. Fabbri and collaborators described a skull that showed a perfectly circular trepanation on the frontal region with no evident associated pathology and a minimal survival span [21]. It was found in a Greek burial site in Sicily. They also reviewed the publications that include the few cases of trepanned skulls found in Italy from the Greco-Roman period. Another cranial remain exhumed in a Roman villa in Rome was described by Mariani-Constantini and collaborators [22]. It consisted of a cranium with a frontal-parietal trepanation of about 5 cm, which was probably made with a chisel and a mallet on a child who showed signs of hydrocephalus and who subsequently survived. These findings, although they are scarce, prove the existence of the practice of trepanning and the different surgical techniques used in that time.

There are also archaeological evidences of contemporary trepanned skulls using techniques that were characteristic of primitive cultures. Tsermoulas and collaborators studied a trepanned skull found in Chios, Greece [23]. The skull shows a left parietal trepanation of 1.6 cm of diameter, which was made by a scraping technique and dated from two centuries after Hippocrates. Novak and collaborators also described a trepanned skull from the fifth century carried out by scraping technique with stone, which was characteristic of primitive cultures [24]. The skull belonged to an individual who was about 50 years of age and shows a great oval frontal-temporal trepanation of 43 × 31 mm on the outer table and 29 × 19 mm on the internal table. There are signs of survival and it was found in a tomb of a Roman archaeological site from the fifth century located in Croatia.

A key point of discussion is the historical origin of Hippocratic trepanations. Due to obvious chronological and geographical reasons, it may seem logical that Greco-Roman trepanation was originally the natural consequence of the evolution of the trepanations performed by previous primitive cultures that settled in the same geographic territory of the Greek peninsula. Nevertheless, there are elements that make them completely different. Firstly, the instruments are undeniably different, although we have no remains from any of the two cases. Hence, in previous primitive cultures of the same geographical areas, cranial trepanations were performed with stone instruments while in the Greco-Roman one they were carried out with iron instruments expressly designed for such purpose. The pictorial representation we have of those surgical instruments is possible thanks to the illustrations from the Renaissance texts that we will discuss later. The designs of these Greco-Roman cranial drilling instruments such as the *'terebra'*, the *'modiolus'* and the *'abaptista'* and the different types of handles are still easily recognisable in many contemporary manual instruments which certainly have nowadays a very occasional use in developed countries. Greek and Roman physicians used the chisel and the mallet as alternative instruments.

However, the biggest difference in comparison with primitive cultures is that Greco-Roman trepanation is done on the basis of certain scientific principles and with a reason and a therapeutic aim that was reflected on the Hippocratic texts. In primitive cultures the lack of documentary and archaeological elements does not allow us to understand the reasons of cranial trepanations. We can only speculate. This does not preclude that ritual or magical cranial trepanations were still carried out in this Greco-Roman period. The limited number of trepanned skulls available and the low frequency of trepanned skulls with a recognisable pathology prevent us from being categorical in one way or the other, although the treatment of head trauma must have probably been the most frequent indication in Greco-Roman trepanations.

Finally, we believe that the greatest value of Greco-Roman trepanation, which was based on the principles of the Hippocratic texts, was probably the fact that it was the cornerstone on which instruments, techniques and indications developed according to a process of continuous improvement. Such process led to modern neurosurgery at the end of the nineteenth century with the osteoplastic craniotomy as a paradigmatic surgical procedure of that surgical specialty. However, the first steps of this long journey were tempestuous because just like in other aspects of culture and science, the European Middle Ages were a dark, critical period concerning medical science and consequently in the history of cranial trepanation.

7.3 Conclusions

The documented origin of trepanation, as it was carried out for centuries until craniotomy was invented, was in the Hippocratic texts of the fourth century BC. There is no documentary or archaeological information that allows us to know how that knowledge solidified in that historic moment but it is clear that it is a consequence of the previous work done by generations of people interested in medicine who became authentic physicians at that point. The Hippocratic and Greco-Roman writings describe accurately the techniques and the instruments needed for cranial trepanations. It is amazing how these contents were copied and translated for almost two millenniums without significant modifications until the Renaissance.

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8 Greco-Roman Surgical Instruments for Trepanation

Different sources of information can be used to know the instruments used in trepanations during the Greco-Roman period. There are archaeological remains of surgical instruments that were found in different locations, such as the ruins of Pompeii and Herculaneum and particularly in the burial sites as the Romans used to include everyday objects among the grave goods. Those instruments can be found in museums and private collections, but unfortunately there are no remains of instruments that could have been used unequivocally or exclusively for cranial trepanation. In these collections we can find instruments that could have been used in bone surgery, such as bone-holding clamps, elevators or chisels, along with scissors, needles, probes, dilators and many surgical instruments with greater or lesser complexity.

In contrast, the descriptions and illustrations of manuscripts and printed texts of the end of the fifteenth century and the beginning of the sixteenth century are the most common source of descriptive and iconographic information about Greco-Roman surgical instruments. However, it is actually an adulterated source of information as they are not the original Greco-Roman writings and, consequently, there is a critical loss of original information. Narrative mistakes tend to accumulate due to the repeated processes of translation, copy and rewriting throughout centuries. This has to be added to the interpretations, contributions and improvements introduced by the authors of the copies and translations. A pertinent feature is that we do not know even if the original manuscripts had figures or plates, and probably they contained no illustrations. In any case, those manuscripts that were copies from the texts attributed to Hippocrates and particularly to Celsus provide very detailed information of the instruments used. However, the printed treatises from the Renaissance already included detailed illustrations of these instruments, although they sometimes seemed to be mere attempts to draw what was described in the text rather than showing real instruments that were familiar or used by the authors or other contemporary physicians in that time. John Stewart Milne made an interesting compilation of the Greco-Roman surgical instruments at the beginning of the twentieth century [1]. He published the book *'Surgical instruments in Greek and Roman times'* in 1907 in which he systematically reviews all the information from museums as well as all bibliographic and etymological data that were available in that time to reconstruct the ancient surgical arsenal. He classifies the instruments and illustrates them with photographs from the museums or images from the classical authors. This work integrated his doctoral thesis, which was presented at the University of Aberdeen and graded with Highest Honours. Other different works that are more modern also address this issue and show photo-

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graphs of the real instruments that were found in the archaeological sites, but in general all of them are based on Renaissance iconography.

An aspect that we must consider when referring to surgical instruments is whether the Greek culture had enough technological capacity to design and manufacture small and delicate instruments such as the *'terebra'* or the *'modiolus'*, especially those with *'abaptista'* mechanisms and interchangeable drilling heads. It is obvious that the remains of jewels and other decorative objects that were found required a thorough metalworking and that both Greeks and Romans had complex instruments for astronomy, sailing, topography and building works. As for surgical instruments, there are archaeological remains of pretty complex tools, such as vaginal dilators or enema cannulas. However, since the working of the Antikythera mechanism (which was discovered in 1900 in a Greek shipwreck) was reconstructed and interpreted in the 70s of the last century it has become clear that the level of sophistication in design and craftsmanship (in significant quantities) of complex instruments was not negligible. The Antikythera mechanism is a complex system of toothed gears that allows intricate and accurate astronomical calculations. It is estimated that it was constructed in the second century BC. The high level of complexity of the Antikythera mechanism guarantees that there were previous, contemporary or subsequently designs and accurate devices with the same or other purposes.

Unfortunately, as we have mentioned, there are no archaeological remains of trepanation instruments although many instruments from different specialties have been found, particularly those used with bone and in general surgery [2, 3]. Many of these instruments might have also been used in cranial trepanation. When reading the Hippocratic texts and Celsus' work we must not forget that the term trepanation must not be applied univocally to cranial drilling. The term trepanation means both drilling the skull and any other bone. Trepanation, as it was used in the Hippocratic texts and Celsus' works, does not exclusively refer to traumatic pathologies either. The book *'On Wounds of the Head'* of the *'Corpus Hippocraticum'* only focuses on cranial injuries and the immediate and late consequences thereof [4]. However, Celsus' *'De Medicina'* talks about trepanation in general terms when referring to diseases, traumas and injuries caused by projectiles that overall affect the bones, making some particular remarks when regarding the skull [5]. By considering these aspects we can better understand the suggested uses of the *'terebra'*, the *'modiolus'* or the *'meningophylax'* instruments.

8.1 Terebra

The *'terebra'* (Gr. τρυπαυου, Lat. *'terebra'*, *'terebella'*) can be defined as an instrument for drilling, a drill or a borer. In the translation of Celsus' work done by W.G. Spencer two types of *'terebra'* are described: *'one like that used by smiths, the other longer in the blade, which begins in a sharp point, suddenly becomes larger, and again towards the other end becomes even smaller than just above the point'*; that is, it can either have a drill bit with a fixed diameter or look like a lancet or a burr. He suggests using it on large injuries that cannot be treated with the *'modiolus'*. In this case it is necessary to carry out several drills around the lesion and join them together with a chisel and a mallet.

The driller could be mounted on a straight handle with a ball on its edge so that it can be firmly held, although a T-shaped handle is more efficient. From a mechanical point of view a brace handle is even more efficient, but it seems that it was not introduced until the sixteenth century. Both Hippocrates 21 and Celsus 8.3 point out that the *'terebra'* had to be cooled down by repeatedly dipping it in cold water, as the heat and the bone sawdust could burn the edges of the bone and make the hole too big. This remark led many subsequent authors to consider that the *'terebra'* should spin around at a higher speed than the one achieved by just manually rotating it. This is why it was stated that they had to have a handle and be connected to an acceleration system. Milne, who transcribed the classical authors, included different methods to accelerate the rotation movements that might have been applied by ancient physicians to the *'terebra'*, particularly the three following examples: a simple leather string around the handle of the driller, a string around the handle of the driller and mounted on an arch and finally, a cross-shaped system with a drilled shank in the centre across which the handle of the driller is placed and strings going from the edges of the shank to the edges of the handle. Milne later questions the efficiency of these systems from a mechanical point of view and their use in mechanical works and craftsmanship of that time. These acceleration systems can be seen illustrated in the first medical texts from the Renaissance. However, they immediately disappeared from such texts.

As for cranial fractures, Celsus 8.3 recommends drilling a borehole next to the fracture line and joining it to the edges thereof by two cuts in a V shape on the bone made with the chisel and the mallet. A similar solution is suggested in Celsus' work 8.5 in order to remove projectiles from the bone that cannot be detached by any other means. We must again consider that the *'terebra'* was an instrument designed for the treatment of diseases and injuries of the bones and its use was not exclusive on the cranium.

8.2 Modiolus

The *'modiolus'* (Gr: χοινίκιον) was clearly defined by Celsus 8.3 in the English version by W.G. Spencer as *'a hollow cylindrical iron instrument with its lower edges serrated; in the middle of which is fixed a pin which is itself surrounded by an inner disc'*. He also describes in detail its correct use. If the edge of the pin is correctly stuck into the bone it can be used directly. Otherwise, it is recommended to make a small hole to place the pin safely so that the *'modiolus'* can spin without sliding. The spinning movement of the serrated crown can be facilitated by means of rose oil or milk, although an excessive amount can cause it to slide. When the physician has started cutting with the *'modiolus'* the central pin can be removed so that they can keep on drilling without it. The depth of the cut is repeatedly determined with a probe until reaching the end of the bone cutting. In that moment, it is recommended to use the *'meningophylax'*, which will be later described. We must remember that the *'modiolus'* was an instrument used generally in the treatment of diseases of the bones and not exclusively on the cranium. There are notes suggesting that it could be even used to access cavities, such as the pleural cavity by perforating the rib cage. Considering the diameter of the driller, in order to achieve its goal, it had to be mounted on a straight thick handle. It would be handled manually, with no rotation accelerators. This driller could also be connected to a brace handle, although as we have mentioned it seems that such handle was not used until many centuries after.

In the medical texts from the Renaissance two types of *'modiolus'* are described: the one with a central pin, which is named in a masculine way or male, whereas the other one that has no pin is named in a feminine way or female. Likewise, these texts describe and illustrate a great number of cuts with different shapes and depth, as well as stopping mechanisms to protect the soft tissues, such as the dura mater and the skull ('*abaptista*'), which are described below.

8.3 Abaptista

The term *'abaptista'* or *'abaptiston'* (Gr. ἀβάπτιστον) refers to the existence of a security system in the driller that avoids invading the intracranial space and injuring the dura mater and the brain and thus any of the soft tissues beneath any bone that is subjected to trepanation. From an etymological point of view, the term *'abaptiston'* is considered to have been created with the prefix particle *'a'* (without) and '*baptiston*' (immersion) and therefore refers to the fact that it cannot be immersed or dipped in the intracranial space. In the drill bit-like '*terebra*' it would consist of a stopping mechanism and in the lancet or burr-like '*terebra*' the driller would just have a greater proximal diameter than the distal part. In the '*modiolus*', the depth control mechanism set forth would be, for example, a second safety crown that would be more external and shorter than the cutting crown. Others say that it would be a mere flange placed at a different distance from the cutting edge. Hence, there were different drillers with a wide range of cutting depths for the different thickness of the cranial bone or the safety crown could also be adapted to the different cutting depths.

The mechanism was described for the first time in Galen's writings. In fact, Galen's greatest technical contribution to cranial trepanation was the *'abaptista'*, which aims to resolve the concern that all classical authors had about protecting the dura mater and consequently the brain during the trepanning process and the removal of osseous fragments. Considering how sophisticated the Antikythera mechanism was, it is not surprising that complex instruments were designed and created for such purpose. Unfortunately, the experts have not discovered so far remains of any of these instruments that let us know the specific stopping mechanism actually used. For this reason, any of the systems that have been set forth afterwards is plausible. Along the next pages, we present a large number of different stopping mechanisms and their designs described thoroughly along centuries.

8.4 Meningophylax

The *'meningophylax'* (Lat. *'membranae custos'*, Gr. μηνιγγοφύλαξ) was an instrument with a small metal plate that was inserted under the bone to protect the underlying soft tissues. It was used to protect not only the dura mater, but also the pleura or other soft structures beneath any bone that was subjected to trepanation before it was finally cut off with the chisel. The most accurate description in W.G. Spencer's translation of Celsus' writings 8.3 was about its particular use on the skull: *'This consists of a plate of bronze, its end slightly concave, smooth on the outer side; this is so inserted that the smooth side is next the brain, and is gradually pushed in under the part where the bone is being cut through by the chisel; and if it is knocked by the corner of the chisel it stops the chisel going further in; and so the surgeon goes on striking the chisel with the mallet more boldly and more safely, until the bone, having been divided all round, is lifted by the same plate, and can be removed without any injury to the brain'*.

8.5 Lenticular

The *'lenticular'* or *'lenticular knife'* is a cutting instrument as it has a blade on one of its sides and a lenticular enlarged area on its end. The enlarged area is placed between the bone and the dura mater once the hole in the skull has been made either naturally by the fracture or disease or artificially by trepanning. The cutting edge allows cutting the bone when it is hammered so that the lenticular enlarged area avoids injuring the dura mater while cutting. When the osseous fragments are lighter they can be cut by manually moving the lenticular in a similar way to the movements made with a knife when peeling.

8.6 Other Surgical Instruments

A myriad of instruments that could be used for bone (and therefore cranial) surgery were described in the Hippocratic texts, as well as in Celsus and Galen's writings. Accordingly, they include tools such as chisels, mallets, saws, tweezers and bone-holding clamps, probes for exploration, scrapers, dissectors or lifters. Other instruments are not specifically described when referring to trepanation but it is assumed that they were used in such procedures, like scalpels, scissors, fine-pointed tweezers, retractors or needles. Some of these instruments have been found in archaeological sites and their use as surgical instruments has been well established.

8.7 Interpretation During the Renaissance of the Instruments Used for Cranial Trepanations in the Greco-Roman Culture

All the written and iconographic information of the surgical instruments that were used in cranial trepanations during the Greco-Roman period come from the first printed medical texts. A forgotten author in this sense is the Italian Vidus Vidius (Guido Guidi, Vido Vidio) (1509–1569) of Florencia, who was physician in Italy and later in France. He is the author of the book *'Chirurgia è Graeco in Latinum conversa, Vido Vidio Florentino interprete, cum nonnullis eiusdem Vidii cõmentariis'*, published in Paris [6]. Vidius makes in this book a commented translation into Latin of some books by Hippocrates, Galen and Oribasius, among them the book by Hippocrates concerning the wounds of the head (*'De vulneribus capitis'*). Here he illustrates the instruments he comments on in the text (Fig. 8.1). This book, and its illustrations, predates the works of della Croce, Paré and Alcázar. It is quite possible that this Vidius book was taken as a basis for some illustrations and comments by the referred authors and many others done later on. The book by Vidius was written almost 1000 years after the fall of the Roman Empire. It is striking, as it happened at the time, that all the drawn instruments are written above their Latin name. The description of the instrument is recorded in the text (Fig. 8.1).

Illustrations include some *'terebra'* with T and brace handles and the three classical acceleration systems, as well as different bone instruments such as lenticular, elevators and tongs. In the first plate are showed page 115 of the book with two saws (*'serrula'*) and a *'modiolus'*; page 116 with two *'terebra'*-type drills, the one on the right with a system that prevents it from sinking; page 117 with a *'Terebra'* with string; and page 118 with '*Terebra'* of bow. The second plate shows page 119 with a *'Terebra'* with transverse handgrip, page 120 with a *'Terebra'* with handle in ball and with transverse handle and page 122 with a *'Terebra'* with brace handle. In this particular illustration the parts of the instruments are itemised (1: hole to house the piercing instruments; 2, 3, 5, 6: handle segments; 4: tube to rotate; 7: top ball; A: semicircular instrument; B: nail-shaped instrument; C: rounded and grooved instrument). The fourth figure in the plate is page 123, with a straight and right-angle chisel. The third plate group page 125 with two curved scrappers, page 126 with a hammer and a cannulated chisel, page 127 with a particular type of scalper or lenticular and page 128 with a lifting lever and a dura mater protector (*'lamina custos membranae'*). Finally, the last plate includes pages 129, with a scissors for resection of bone fragments, and 130 with a bone forceps.

Vidius represents in this book all types of existing handles: brace, straight, handgrip and those with accelerating systems. The book is a comment translation to Latin of the book by Hippocrates *'De vulneribus capitis'*. However, as we have stated, it has been not demonstrated that Greco-Roman surgeons have used brace handles. This demonstrates that the Renaissance authors actually illustrate in their books the instruments that were used by themselves in their time.

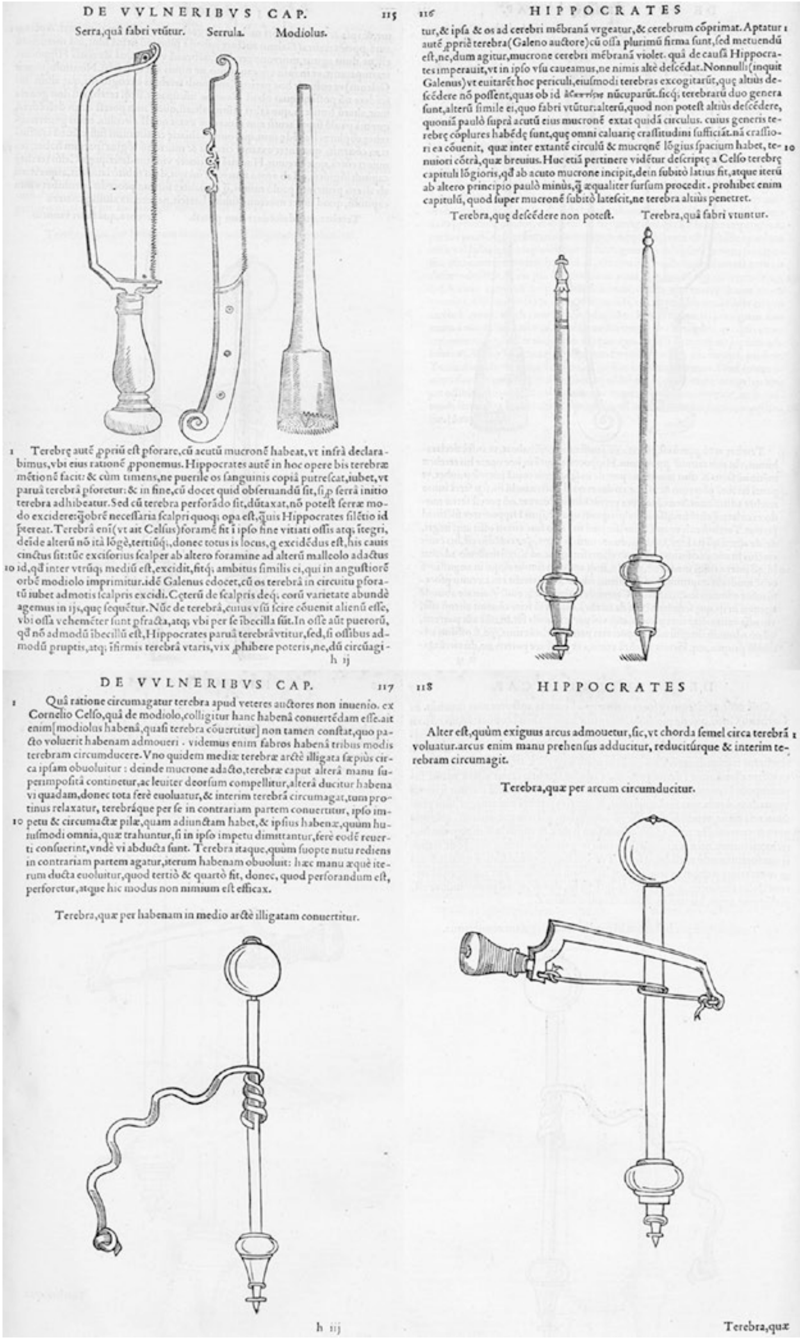
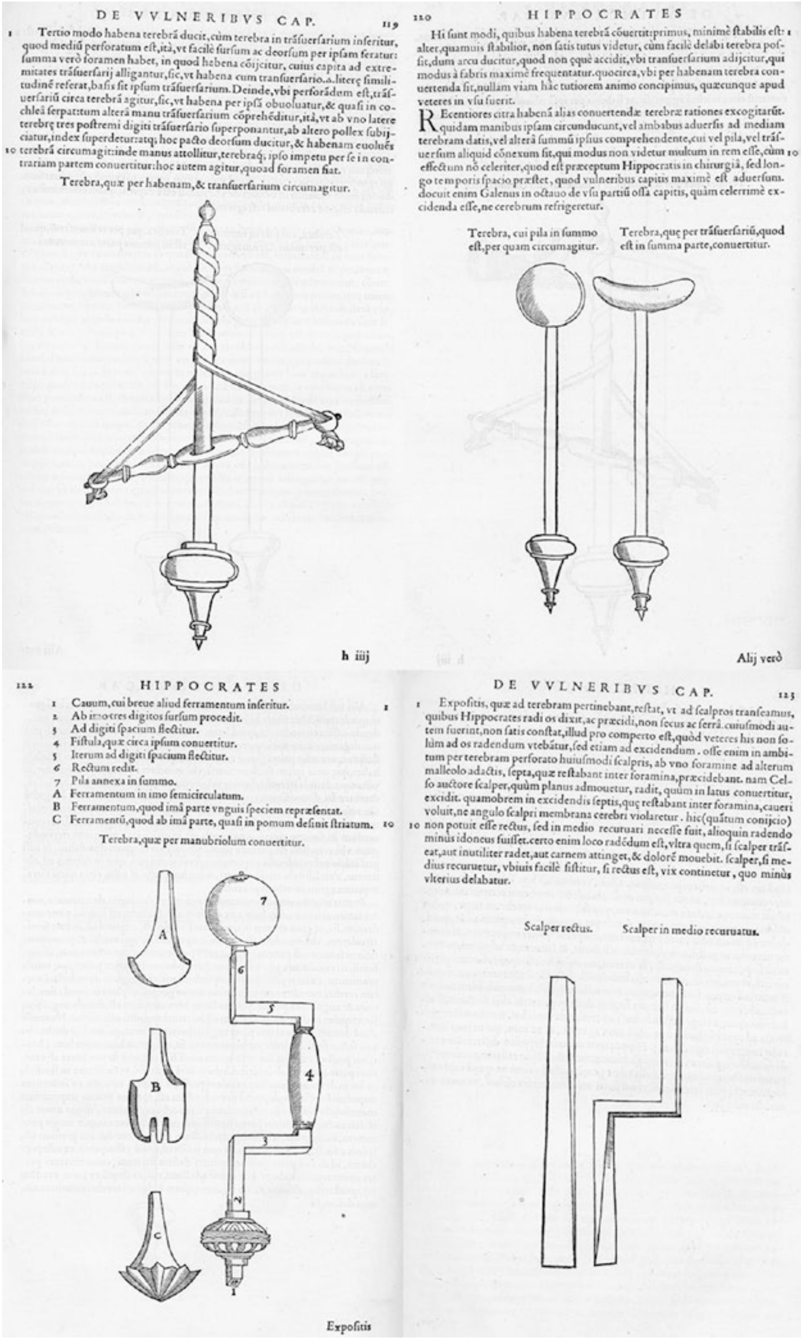


Fig. 8.1 Greco-Roman instruments related to trepanation illustrated by Vidius (Vidius V. Chirurgia è Graeco in Latinum conversa, Vido Vidio Florentino interprete cum nonnullis eiusdem Vidii cõmentariis. Paris, 1544)



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Tertio modo habena terebrã ducit, cùm terebra in trãſuerſarium inſeritur, quod mediũ perforatum eſt, ità, vt facilè ſurſum ac deorſum per ipſam feratur: ſumma verò foramen habet, in quod habena cõijcitur, cuius capita ad extremitates trãſuerſarij alligantur, ſic, vt habena cum tranſuerſario .a. literę ſimilitudinẽ referat, baſis ſit ipſum trãſuerſarium. Deinde, vbi perforãdum eſt, trãſuerſariũ circa terebrã agitur, ſic, vt habena per ipſã obuoluatur, & quaſi in cochleã ſerpat: tum alterã manu trãſuerſarium cõprehẽditur, ità, vt ab vno latere terebrę tres poſtremi digiti trãſuerſario ſuperponantur, ab altero pollex ſubijciatur, index ſuperdetur: atq; hoc pacto deorſum ducitur, & habenam euoluẽs terebrã circumagit: inde manus attollitur, terebraq; ipſo impetu per ſe in contrariam partem conuertitur: hoc autem agitur, quoad foramen fiat.

Terebra, quæ per habenam, & tranſuerſarium circumagitur.

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Hi ſunt modi, quibus habena terebrã cõuertit: primus, minimè ſtabilis eſt: alter, quamuis ſtabilior, non ſatis tutus videtur, cùm facilè delabi terebra poſſit, dum arcu ducitur, quod non ęquè accidit, vbi tranſuerſarium adijcitur, qui modus à fabris maximè frequentatur. quocirca, vbi per habenam terebra conuertenda ſit, nullam viam hàc tutiorem animo concipimus, quæcunque apud veteres in vſu fuerit.

Recentiores citra habenã alias conuertendæ terebræ rationes excogitarũt. quidam manibus ipſam circunducunt, vel ambabus aduerſis ad mediam terebram datis, vel alterã ſummũ ipſius comprehendente, cui vel pila, vel trãſuerſum aliquid cõnexum ſit, qui modus non videtur multum in rem eſſe, cùm effectum nõ celeriter, quod eſt præceptum Hippocratis in chirurgiã, ſed longo temporis ſpacio præſtet, quod vulneribus capitis maximè eſt aduerſum. docuit enim Galenus in octauo de vſu partiũ oſſa capitis, quàm celerrimè excidenda eſſe, ne cerebrum refrigeretur.

Terebra, cui pila in ſummo eſt, per quam circumagitur.

Terebra, quę per trãſuerſariũ, quod eſt in ſumma parte, conuertitur.

Alij verò

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1 Cauum, cui breue aliud ferramentum inſeritur.
2 Ab imo tres digitos ſurſum procedit.
3 Ad digiti ſpacium flectitur.
4 Fiſtula, quæ circa ipſum conuertitur.
5 Iterum ad digiti ſpacium flectitur.
6 Rectum redit.
7 Pila annexa in ſummo.
A Ferramentum in imo ſemicirculatum.
B Ferramentum, quod imã parte vnguis ſpeciem repræſentat.
C Ferramentũ, quod ab imã parte, quaſi in pomum deſinit ſtriatum.

Terebra, quæ per manubriolum conuertitur.

Expoſitis

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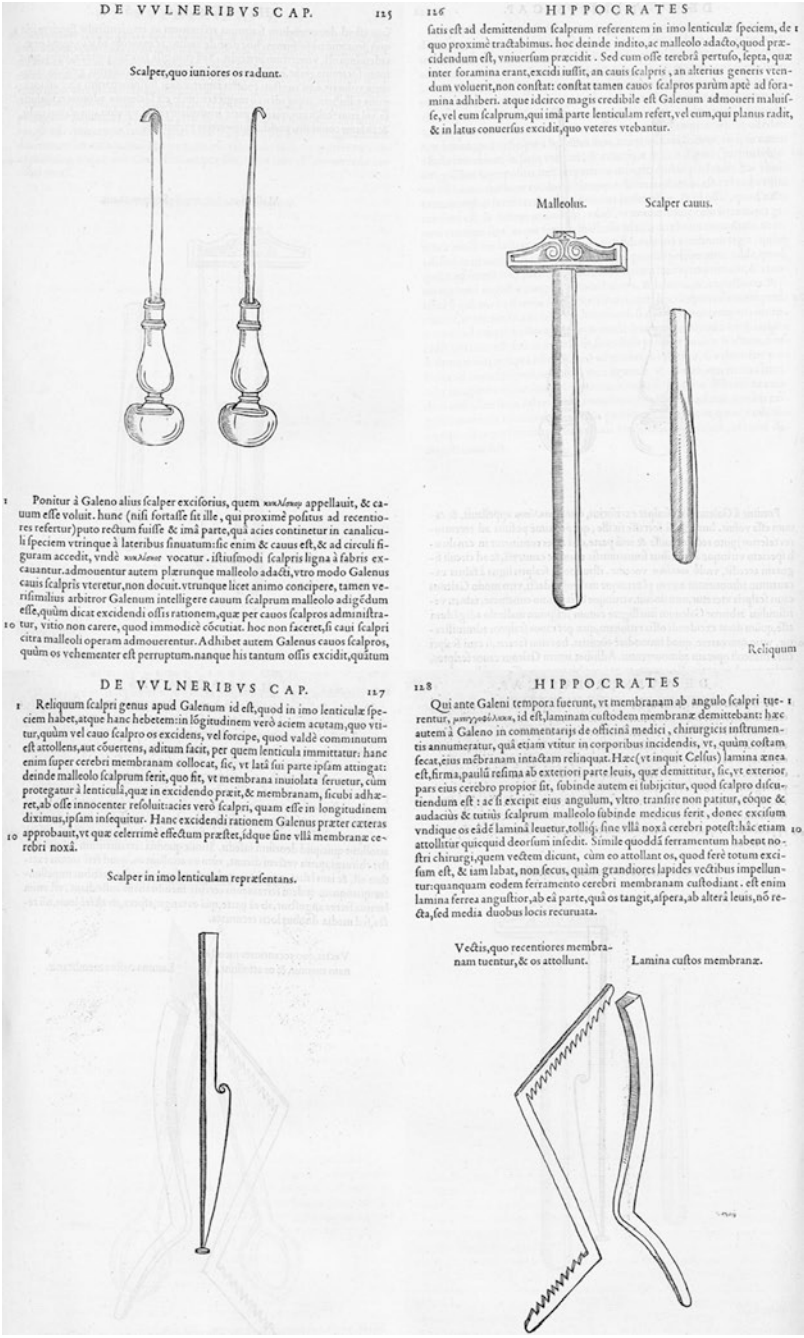
Expoſitis, quæ ad terebram pertinebant, reſtat, vt ad ſcalpros tranſeamus, quibus Hippocrates radi os dixit, ac præcidi, non ſecus ac ſerrã. cuiuſmodi autem fuerint, non ſatis conſtat, illud pro comperto eſt, quòd veteres his non ſolùm ad os radendum vtebãtur, ſed etiam ad excidendum. oſſe enim in ambitum per terebram perforato huiuſmodi ſcalpris, ab vno foramine ad alterum malleolo adactis, ſepta, quæ reſtabant inter foramina, præcidebant. nam Celſo auctore ſcalper, quùm planus admouetur, radit, quùm in latus conuertitur, excidit. quamobrem in excidendis ſeptis, quę reſtabant inter foramina, caueri voluit, ne angulo ſcalpri membrana cerebri violaretur. hic (quãtum conijcio) non potuit eſſe rectus, ſed in medio recuruari neceſſe fuit, alioquin radendo minùs idoneus fuiſſet. certo enim loco radẽdum eſt, vltra quem, ſi ſcalper trãſeat, aut inutiliter radet, aut carnem attinget, & dolorẽ mouebit. ſcalper, ſi medius recuruetur, vbiuis facilè ſiſtitur, ſi rectus eſt, vix continetur, quo minùs vlterius delabatur.

Scalper rectus.

Scalper in medio recuruatus.

Fig. 8.1 (continued)



DE VVLNERIBVS CAP. 125

Scalper, quo iuniores os radunt.

Ponitur à Galeno alius ſcalper exciſorius, quem κυκλίσκον appellauit, & cauum eſſe voluit. hunc (niſi fortaſſe ſit ille, qui proximè poſitus ad recentiores refertur) puto rectum fuiſſe & imâ parte, quâ acies continetur in canaliculi ſpeciem vtrinque à lateribus ſinuatum: ſic enim & cauus eſt, & ad circuli figuram accedit, vndè κυκλίσκος vocatur. iſtiuſmodi ſcalpris ligna à fabris excauantur. admouentur autem plærunque malleolo adacti, vtro modo Galenus cauis ſcalpris vteretur, non docuit. vtrunque licet animo concipere, tamen veriſimilius arbitror Galenum intelligere cauum ſcalprum malleolo adigēdum eſſe, quùm dicat excidendi oſſis rationem, quæ per cauos ſcalpros adminiſtratur, vitio non carere, quod immodicè cōcutiat. hoc non faceret, ſi caui ſcalpri citra malleoli operam admouerentur. Adhibet autem Galenus cauos ſcalpros, quùm os vehementer eſt perruptum. nanque his tantum oſſis excidit, quātum

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ſatis eſt ad demittendum ſcalprum referentem in imo lenticulæ ſpeciem, de quo proximè tractabimus. hoc deinde indito, ac malleolo adacto, quod præcidendum eſt, vniuerſum præcidit. Sed cum oſſe terebrâ pertuſo, ſepta, quæ inter foramina erant, excidi iuſſit, an cauis ſcalpris, an alterius generis vtendum voluerit, non conſtat: conſtat tamen cauos ſcalpros parùm aptè ad foramina adhiberi. atque idcirco magis credibile eſt Galenum admoueri maluiſſe, vel eum ſcalprum, qui imâ parte lenticulam refert, vel eum, qui planus radit, & in latus conuerſus excidit, quo veteres vtebantur.

Malleolus. Scalper cauus.

Reliquum

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Reliquum ſcalpri genus apud Galenum id eſt, quod in imo lenticulæ ſpeciem habet, atque hanc hebetem: in lōgitudinem verò aciem acutam, quo vtitur, quùm vel cauo ſcalpro os excidens, vel forcipe, quod valdè comminutum eſt attollens, aut cōuertens, aditum facit, per quem lenticula immittatur: hanc enim ſuper cerebri membranam collocat, ſic, vt latâ ſui parte ipſam attingat: deinde malleolo ſcalprum ferit, quo fit, vt membrana inuiolata ſeruetur, cùm protegatur à lenticulâ, quæ in excidendo præit, & membranam, ſicubi adhæret, ab oſſe innocenter reſoluit: acies verò ſcalpri, quam eſſe in longitudinem diximus, ipſam inſequitur. Hanc excidendi rationem Galenus præter cæteras approbauit, vt quæ celerrimè effectum præſtet, idque ſine vllâ membranæ cerebri noxâ.

Scalper in imo lenticulam repræſentans.

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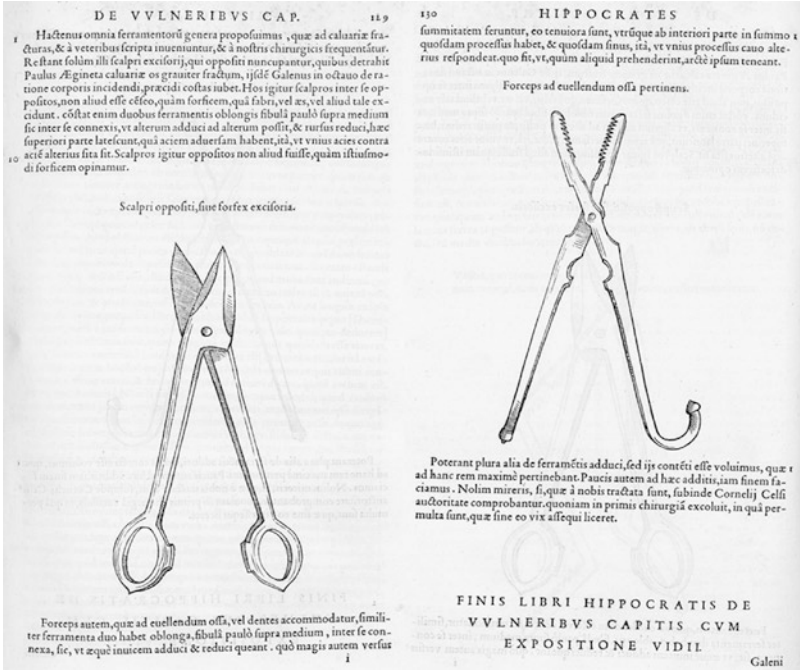
Qui ante Galeni tempora fuerunt, vt membranam ab angulo ſcalpri tuerentur, μηνιγγοφύλακα, id eſt, laminam cuſtodem membranæ demittebant: hæc autem à Galeno in commentarijs de officinâ medici, chirurgicis inſtrumentis annumeratur, quâ etiam vtitur in corporibus incidendis, vt, quùm coſtam ſecat, eius mēbranam intactam relinquat. Hæc (vt inquit Celſus) lamina ænea eſt, firma, paulū reſima ab exteriori parte leuis, quæ demittitur, ſic, vt exterior pars eius cerebro propior ſit, ſubinde autem ei ſubijcitur, quod ſcalpro diſcutiendum eſt: ac ſi excipit eius angulum, vltro tranſire non patitur, eóque & audaciùs & tutiùs ſcalprum malleolo ſubinde medicus ferit, donec exciſum vndique os eâdē laminâ leuetur, tolliq; ſine vllâ noxâ cerebri poteſt: hâc etiam attollitur quicquid deorſum inſedit. Simile quoddā ferramentum habent noſtri chirurgi, quem vectem dicunt, cùm eo attollant os, quod ferè totum exciſum eſt, & iam labat, non ſecus, quàm grandiores lapides vectibus impelluntur: quanquam eodem ferramento cerebri membranam cuſtodiant. eſt enim lamina ferrea anguſtior, ab eâ parte, quâ os tangit, aſpera, ab alterâ leuis, nō recta, ſed media duobus locis recuruata.

Vectis, quo recentiores membranam tuentur, & os attollunt. Lamina cuſtos membranæ.

Fig. 8.1 (continued)



DE VVLNERIBVS CAP. 129

Hactenus omnia ferramentorũ genera propoſuimus ,quæ ad caluariæ fracturas,& à veteribus ſcripta inueniuntur,& à noſtris chirurgicis frequentátur. Reſtant ſolùm illi ſcalpri exciſorij,qui oppoſiti nuncupantur,quibus detrahit Paulus Ægineta caluariæ os grauiter fractum, ijſdẽ Galenus in octauo de ratione corporis incidendi,præcidi coſtas iubet. Hos igitur ſcalpros inter ſe oppoſitos,non aliud eſſe cẽſeo,quàm forficem,quâ fabri,vel æs,vel aliud tale excidunt. cõſtat enim duobus ferramentis oblongis fibulâ paulò ſupra medium ſic inter ſe connexis,vt alterum adduci ad alterum poſſit,& rurſus reduci,hæc ſuperiori parte lateſcunt,quâ aciem aduerſam habent,ità,vt vnius acies contra aciẽ alterius ſita ſit. Scalpros igitur oppoſitos non aliud fuiſſe,quàm iſtiuſmodi forficem opinamur.

Scalpri oppoſiti,ſiue forfex exciſoria.

Forceps autem,quæ ad euellendum oſſa,vel dentes accommodatur,ſimiliter ferramenta duo habet oblonga,fibulâ paulò ſupra medium , inter ſe connexa, ſic, vt æquè inuicem adduci & reduci queant . quò magis autem verſus

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ſummitatem feruntur, eo tenuiora ſunt, vtrũque ab interiori parte in ſummo quoſdam proceſſus habet, & quoſdam ſinus, ità, vt vnius proceſſus cauo alterius reſpondeat. quo fit,vt,quùm aliquid prehenderint,arctè ipſum teneant.

Forceps ad euellendum oſſa pertinens.

Poterant plura alia de ferramẽtis adduci,ſed ijs contẽti eſſe voluimus, quæ ad hanc rem maximè pertinebant. Paucis autem ad hæc additis,iam finem faciamus . Nolim mireris, ſi,quæ à nobis tractata ſunt, ſubinde Cornelij Celſi auctoritate comprobantur. quoniam in primis chirurgiã excoluit, in quâ permulta ſunt,quæ ſine eo vix aſſequi liceret.

FINIS LIBRI HIPPOCRATIS DE VVLNERIBVS CAPITIS CVM EXPOSITIONE VIDII.

Galeni

Fig. 8.1 (continued)

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9 Greco-Roman Surgical Techniques and Indications of Trepanation

9.1 Hippocrates's Proposals

The book *'On Wounds of the Head'* from the *'Corpus Hippocraticum'* addresses the treatment of cranial wounds and fractures and particularly cranial trepanation as a treatment method for cranial fractures. In this section we describe the recommendations gathered in such book, adapting them to modern neurosurgical terminology and vision, and following the translation into English in 1868 by Charles Darwin Adams [1].

The text recommends making some general considerations of particular clinical interest before a trepanation is indicated. The first step consists of examining the injured person, locating in which part of the head is the wound and removing the hair from it to determine whether the bone is just exposed or also fractured. If there is any doubt, a probe shall be used. The patient must be asked about the type of trauma in order to look for other skull injuries that are distant from the point of impact. The type of trauma and the energy of the impact must be assessed as well. Therefore, it is highlighted that tangential impacts are less capable of causing fractures; that direct impacts caused by round and heavy objects bruise the skin and the bone; and that sharp and long objects make neat wounds with linear fractures or bone indentations.

Those wounds in the head that affect areas that are covered with hair must not be treated with liquids, ointments, poultices, dressings or bandages, unless they require an incision. Wounds on the forehead, above the eyebrows and on other areas without hair are treated with bandages that are removed once the inflammation and the swelling have disappeared. The wounds that require incision are those with a small size that does not allow local treatment or examining the region of the skull beneath them to confirm a fracture, or those cases in which the skin is bruised or ulcerated. These wounds can be incised without consequences in any part of the head, excepting for the temporal area and above it. If the person who is treated like this experience's seizure, such seizures will appear on the right side if the incision has been made on the left temple and vice versa. In case of fractures, the skin incision must be large and the bone must be denuded from the membranes that cover it. The wound is now filled with a paste made of boiled wheat flour or mixed with vinegar. It has to be soggy. The following day the mass is removed and the exposed bone is systematically examined by touching it, by visual observation or with a scraper in search of the fracture.

When the physician decides to drill the bone after this cranial examination he puts the paste again on the wound and the surgery is carried out 3 days after. However, the intervention must not be postponed if any of these circumstances applies: signs of a cranial fracture or contusion or both, when the weapon or otherwise the person that has caused the wound is heavy or strong, and

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finally when the patient experiences vertigo, vision loss or stupor and loses consciousness. In those cases, in which it is not clear whether there is fracture or not, the physician applies a paste made of tar and a bandage that will be removed the following day. At this stage, if there is a fracture, it will be stained in black whereas the healthy bone without fracture remains white.

When there is a line of fracture it has to be scrapped with a scraper. The treatment is over when the fracture line disappears, although the bone is bruised beneath. If the fracture is deeper a trepanation must be carried out. The bone, just like scalp tissues and the dura mater itself, can become inflamed, fester or produce granulation tissue. Hence, they must always be kept and left dry and clean. Those fractured bone fragments that have no blood supply and get dried, that are devitalised and become 'shell pieces' and that detach from the rest of the viable bone must be removed during the dressing change procedures. If the fragments are depressed and their size is big they can be easily handled if the dura mater is complete. If they are small and numerous it is even easier. Many fragments are removed when they are lifted due to the underlying inflammation or granulation. If the wound is kept dry and clean after festering the prognosis will be good. These fractures must not undergo trepanation in any case.

The trepanation with the serrated instrument (*'modiolus'*) is described in the first place. In case of performing a trepanation from the beginning, the first recommendation is not to reach the dura mater to keep its integrity and not to widely expose it, so that no granulation tissue is formed. It is also recommended to leave a fine layer of bone with the aim of protecting the dura mater. It will not cause any problem and will eventually detach. On the contrary, if the trepanation is performed later, it must be carried out with a serrated instrument in order to reach the dura mater. To do so, the *'modiolus'* is repeatedly removed and the hole is palpated with a probe to check its depth as the bone can have a variable thickness in the different areas of the skull. The same must be done when the trepanation is carried out from the beginning and the physician decides to separate the bone from the dura mater. Finally, the text refers to the trepanations carried out with a driller (*'terebra'*) and highlights that in case the physician's first intention is to trepan a fine layer of bone must be left. Under no circumstances the dura mater can be reached. During the trepanning process, the trepan must be often removed and dipped in cold water as the bone warms up so much that it ends up drying and getting burnt, obtaining a bigger hole in the skull than the ideal one.

Regardless of whether a wound has been trepanned or not, a painful, bright, reddish oedema might appear on the forehead and the eyes along with fever. If the wound looks good and the patient seems fit, the physician only has to give them a bowel purgative so that they evacuate the bile. This way the fever and the inflammation will disappear and the patient will evolve favourably.

When a patient suffers from a deadly wound, the physician must know what the symptoms and the evolution are. When the skull is fractured and due to negligence, it has been determined that the bone is complete and therefore the injury has not been treated or trepanned, the patient starts showing fever and the wound will experience inflammatory changes, suppuration, sloughs and necrosis. The patient will develop mouth sores and delirium, which will lead to death. If there are seizures, they will appear on the contrary side of the wound. The patient dies before 7 days in the summer months and before 14 days in winter. If the surgeon notices the fever or any of the accompanying symptoms, it is indicated to saw or remove the bone to the dura mater with the aim of solving the bad evolution. This procedure is now easier.

Once we know the Hippocratic standpoint and strategy about the general treatment of cranial wounds and fractures and the indications of trepanation, there are many issues that can be discussed from a modern neurosurgical point of view. Firstly, the text only refers to wounds on the head, with or without cranial fracture, and their treatment. This is not a general text on cranial or brain injuries. Instead, it addresses cranial traumas caused by direct impact, normally with a scalp wound and often with a subjacent cranial fracture. In this regard, we must highlight the accurate remarks on the importance of the mechanism by which the injuries were caused according to the traumatic agent, the type of impact and the energy thereof. A second aspect is how difficult it is to understand the different types of cranial fractures to which they refer, particularly when addressing *'hydra'* traumas. On the other side, the fact that they identified injuries that were distant from the point of impact of the main trauma, whether they were caused by associated direct traumas or whether they were authentic 'contrecoup lesions', is remarkable. A third comment refers to the benefits of trepanations on fractures. Nowadays we know that most cranial fractures do not require surgical treatment, excepting from certain depressed fractures. However, the surgical treatment criteria for open fractures are much wider. Current experience proves that treating an open or closed linear fracture has no benefit, unless an uncommon associated epidural haematoma is shown. The same applies to depressed or non-depressed comminuted fractures, excepting for aesthetic reasons, communication with septic cavities or open fractures, or suspected or evidenced break of the dura mater or a brain wound due to the osseous fragments. Some of these problems would be solved with the bone-handling techniques described in the book '*On Wounds of the Head*' from the *'Corpus Hippocraticum'*, especially when it suggests removing osseous fragments. However, scrapping fissures, bruises or linear fractures of the outer table, as it is set forth, do not have any benefit for the patient. The same is applied for trepanning the bone while leaving in place the internal table. In view of the current criteria, it is curious that cranial surgery was formally contraindicated in comminuted and depressed fractures.

In our opinion, trepanations were certainly carried out according to some reasons that were completely different to the ones we now hold. A sign thereof was the treatment of the cranial fracture itself to remove it. It included scrapping, lifting the fragments, removing the bone fragments or trepanning. It was probably done that way because the symptoms of brain commotion or concussion from which patients occasionally suffered were considered to be caused by the fracture itself. The treatment of the fracture and its removal by scrapping or trepanning, which is completely ineffective on its own, were considered to be the reasons for the patient's clinical improvement (when they improved). It is obvious that it would have healed anyway without needing any action on the fracture. It has also been considered that the treatment of fractures could result into the cleaning thereof. This would prevent later complications or the sporadic evacuation of an epidural haematoma found by chance.

The other alternative explanation is that trepanations would have a major role in the treatment of delayed complications of the trauma rather than the primary or secondary traumatic injury itself, particularly in the treatment of infections. The passages of the text that can be related to infections are the following: the text only addresses wounds of the head (that are always contaminated); pretty long periods of time are established to act on the bone from the starting moment of the treatment without referring to the moment of the trauma (the infection requires some time); it is obsessively recommended to scrap fissures, linear fractures and bone contusions (this way devitalised tissues would be removed and the grooves in which infections could occur with ease would be smoothed); a trepanation performed from the beginning must leave the internal table intact, whereas a later trepanation must reach the dura mater (the later it is done, the more extended osteitis it shows); the writings set forth that it is easier to remove the bone in a deferred trepanation (a bone with osteitis is softer); and, finally, the only clinical complications described can be understood as a local infection with good prognosis or a severe local infection that leads to a sepsis and the death of the patient. Taking into consideration all these assumptions, if we reread the writings of the book *'On Wounds of the Head'* from the *'Corpus Hippocraticum'* and we apply them to the treatment of infected open fractures everything will seem more comprehensible.

9.2 Celsus's Proposals

Unlike Hippocrates, we must advise that Cornelius Celsus (25 BC–50 AC), when addressing this issue, mostly refers to non-traumatic injuries that are located in any bone, although he sometimes expressly refers to the skull [2]. Celsus considers that a diseased bone can be removed in two ways. When the injury is small the *'modiolus'* is used. The pin is introduced in a place, so that the cutting crown covers all the affected bone. If the injury is not evident, a notch is made by means of the chisel in order to introduce the pin. When the injury is large enough and cannot be covered by the *'modiolus'* it is necessary to use the *'terebra'*, surrounding the injury and making drills that are not too separated from each other. The spaces between the drills are removed by means of a chisel and a mallet, obtaining thus a detachable piece of bone similar to the one obtained with the *'modiolus'* but with a bigger size. If the edges of the bone still show an evident injury or any additional lesion detected by the probe, the bone will be cut out as much as it is necessary. In order to protect the soft tissues beneath the bone, particularly the dura mater, the driller will be repeatedly removed and the hole will be checked with a probe. When reaching the soft areas after completely drilling the bone, like the dura mater, the *'meningophylax'* will be used as a protection. In this case all the bone sawdust and fragments must be removed so that the edges of the osseous resection are neat. When only the superficial layer of the bone (the outer table when referring to the skull) has been removed and the deep layer is kept, the bone must be smoothed in order to allow the scar to fill in the hole left by the surgery if the wound is appropriately cleaned and dressed.

Before explaining the techniques, Celsus describes the symptoms and the clinical signs related to the cranial trauma, selection of the treatment point, use of bandages and local and general treatments. We must highlight the importance given to injuries distant from the point of impact and those fissures that are unnoticed in a first physical examination and require dyes in order to be found. He also discusses the possible confusion between fracture lines and cranial sutures because, as he states, cranial sutures are not always located in the same place. Making an incision large enough, with the shape of a cross, the fracture is exposed. Contrary to ancient authors, Celsus suggests trying from the very beginning a medical treatment with pastes for open fractures. If things are doing well, 5 days after the fracture the wound will fill in with a callosity or a scab that protects the brain, even though the edges are a bit separated. If things go wrong and the patient keeps on having fever and starts showing delirium, drainage from the wound, swollen cervical lymph nodes, pain and food aversion the best option is to trepan in the end.

Traumas of the bones may cause fractures or not. Scrapping and smoothing the bone treat bone indentations or roughness. This is particularly frequent in the head. A blow to the head can cause a linear fracture or a depressed comminuted fracture. Depressed bone fragments can press or break the dura mater and irritate the brain. For this reason, it is advisable to treat them, although the physician must remove as little as possible from the bone. If the fragments are overlapped, a chisel is used to remove the upper fragment. However, when fragments are imbricated it is necessary to use the *'terebra'*. Thus, a hole is made about a centimetre from the edge of the fracture line and this is joined in a V shape with two lines made with the chisel. It is possible to make two or more holes, performing thus a polygonal or crescent cranial resection. Uneven or devitalised fragments are cut and removed with tweezers. Small fragments will be removed later, when cleaning and dressing the wound. The osseous resection must be very limited as the brain is better protected with the bone than without it. The dura mater is cleaned with vinegar and the blood clots are removed.

A special type of trepanation described by Celsus is the one required for removing projectiles from the bone. The first step is trying to remove them with tweezers, just like it was a tooth. If this is not possible, a burr hole is made and it is joined with two lines made with a chisel to the entrance point of the projectile, which is now easily removed. These recommendations generically refer to projectiles that have hit the bone, but they can apply to those located inside the skull.

The trepanation was carried out with the *'terebra'* or the *'modiolus'*, depending on the type of injury. Celsus 8.3 described two types of *'terebra'*, one with a drill bit that had a fixed diameter and other in the shape of a lancet or a burr. He also described the *'modiolus'* as a cylindrical hollow instrument that had a lower serrated edge and a central pin. The pin is stuck into the bone or a small hole is made to place the pin safely so that the *'modiolus'* can spin without sliding. In order to make easier the spinning movement of the serrated crown rose oil or milk is used. This also avoids the instrument to warm up and burn the bone, although an excessive amount can cause it to slide. When the physician has started cutting with the *'modiolus'* the central pin can be removed so that they can keep on drilling without it. In order to protect the membranes beneath the bone, i.e. the dura mater when referring to the skull, the instrument will be repeatedly removed and the hole will be checked with a probe.

When a large opening is required or the *'modiolus'* cannot be used, two or more drills are made with the *'terebra'*, being careful with the underlying soft tissues (the dura mater in the skull) just like before to avoid injuring them. To remove the bone, it is necessary to cut the spaces between the drills with the chisel and the mallet. Now it is the time to use the *'meningophylax'* in order to protect the underlying soft tissues during this procedure. The remaining bone fragments are removed with tweezers or the chisel. The margins of the trepanation must be neat and smooth.

In order to better understand Celsus' descriptions we need to abandon the idea that they exclusively refer to cranial wounds and fractures. The available texts repeatedly allude to diseases of the bones, which were translated by W.G. Spencer as 'caries'. We need to remember that in the nineteenth century surgery treatises used the term caries to mean destructive lesions of the bone, such as chronic infections or tumours. In other sections Celsus expressly refers to traumatic injuries of the bones with different types of fractures. In both cases, he sometimes makes a special reference to cranial injuries and fractures. The same happens when referring to the trepanation technique, which is described in general for any bone, although there are particular remarks for the cranium. Lastly, we must make the same considerations when focusing on the instruments, which were generic for any trepanation on any bone, although some terms are now correctly related to surgical actions on the skull, such as the trepan, or mistaken, such as the *'meningophylax'*.

9.3 Aegineta's Proposals

The details of the techniques and the instruments are not significant in the work by Paulus Aegineta (625–690?) but problems faced when treating cranial fractures are described. The concepts that were previously explained by Hippocrates or Celsus are again repeated centuries later without greater details or personal contributions. We are going to follow the F. Adam's English version of Paulus Aegineta's work VI.XC to describe them [3].

Paulus Aegineta considers several types of cranial fractures and makes a different classification thereof. The types of fractures are fissure, incision, expression (the bone breaks into many pieces which dip over the meninx), depression (the bone breaks into many pieces and now dip beneath the meninx), an arched fracture (the fracture has a raised part in the centre and it is depressed around it), a capillary fracture (in which the break is so small that it is not easily noticeable) and indentation (depression of the bone without a fracture, especially frequent in children). He also speaks of those fractures that are located in a different place than the one that the patient has been stricken. The fracture is diagnosed according to the characteristics of the trauma, the symptoms such as vertigo, loss of speech and confinement to bed, by direct visualisation through the wound of the head or by enlarging it. In case of capillary fractures, they are diagnosed after introducing black ink and scrapping the bone afterwards.

Treatment depends on the type of fracture. In case of capillary fractures, he suggests scrapping them until the fracture disappears. In fissures the physician has to scrap until reaching the required depth. If the fracture only reaches the diploe it is not necessary to go deeper. If there are bone fragments, they must be removed by means of the appropriate instruments. In other cases, when reaching the meninx by scrapping it has to be determined whether the fracture is stuck on the dura mater or not. If so, the patient shows moderate inflammation and pus formation and the fever gradually subsides. If the membrane is detached from the bone the prognosis is bad and the patient will show pain, fever, a change of the colour of the bone and pus. In this case, if a cranial drill is not made ominous symptoms will appear such as bilious vomiting, seizures, disorders of intellect and high fever.

The intervention must be carried out before 14 days in the winter months and before 7 days in summer if there is no other cause that justifies it. The head is shaved, and X-shaped incision is made and the bone is denuded. A paste is applied, as well as gauzes and bandages. The skull is trepanned the following day and the patient is prepared with cotton balls in their ears. The dressings are removed and the wound is opened. The assistants will separate the margins. If the bone is loosened the fragments will be lifted and removed. The chisel and the mallet are initially used but if the bone is too hard it can be drilled with a driller called *'abaptista'* which has some protuberances that prevent it to dip in the meninx. The physician uses now the chisel to break the bone into pieces and take them out with the fingers or the suitable instruments. The *'lenticular'* is highlighted by Paulus Aegineta, as he describes in detail how it is used. It is praised as according to F. Adams's words: *'this is the more common, and at the same time the easiest and least dangerous mode of operating; but the method of performing it with a sort of incisor called lenticular is greatly praised by Galen, being performed without perforation after the part has been scraped'*. He prefers it rather than other methods and says that *'the mode of operating with saws and the instruments called chosnicides or modioli (trepans?) is condemned by the moderns as a bad one'*. An original aspect is that he refers to the amount of fracture that is to be treated by saying that it is not necessary to be exhaustive when trying to reach it all and that whenever it is not accessible there is no danger if we do not treat it (*'we must not pursue them to their termination, well knowing that no harm will result from them'*).

Paulus Aegineta represents the last link of Greek medicine before the Islamic dominance of Byzantium. He gathered all the medical knowledge of that time by following all what had been described by Hippocrates, Celsus and Galen. In F. Adams' text it is clearly admitted that the aim of treating fractures was to eliminate them surgically by scrapping or removing osseous fragments that could be loose or after preparing them with the chisel and the mallet, the lenticular or, exceptionally, with additional drills on the skull. The discussion about the amount of fracture to be treated reasserts that fractures were considered to be the reason for the patient's symptoms and that the purpose of surgery was removing them. As we have alluded, the terminology of the drilling systems used by Paulus Aegineta is not well defined in F. Adams' text and might cause confusion to the reader.

9.4 Illustrative Case

At that time there were no case reports in the medical texts to be discussed and the historical documents are scarce. We include in this section one of the fictitious cases operated on by Sinuhe in the novel by Mika Waltari, where the author tries to describe an imaginary Egyptian trepanation using wrongly as Egyptians a lot of techniques and instruments introduced centuries later and actually belonged to the Greco-Roman heritage [4].

9.4.1 Nobleman Trepanned by Sinuhe

We describe one of the cases of trepanation that Sinuhe carries out as described in the book *'Sinuhé egyptiläinen'*, written by the Finnish author Mika Waltari (1908–1979). The novel describes with some details the trepanation performed on a nobleman who complained about hearing the sound of the sea inside his head, fainting and losing consciousness and experiencing excruciating headaches. All these symptoms were so unbearable that he wanted to die. When palpating the skull Sinuhe did not find any evidence of significance but when it came to tapping the head with a mallet he identified a point where the nobleman shrieked and fainted. The general technique used by Sinuhe to operate on the patient is described below. The surgeon washes both his hands and the instruments. The head is shaved and an ointment is applied. The patient is given a narcotic ('wine mixed with anaesthetics'), but in spite of that he must be restrained and firmly tied up, fitting the head on a support. After cutting the scalp, the bleeding was controlled by means of cauterisation and medicines, although there is also a 'haemostatic man' near the patient. After the skull is exposed, a large piece of it is lifted with the trepan, saw and tweezers. Beneath the bone there is 'ugly reddish' lesion with a size similar to a swallow egg that is removed after cauterising all what connects it to the brain. The cranial defect is repaired with a silver plate that meanwhile has been prepared by taking the removed piece of bone as a model. It is fastened with some hooks. The skin is sutured. Once the surgery is over, the patient, who has not lost consciousness, stands up and verifies that the noise has disappeared and that he has no headaches any longer. The patient has an excellent evolution at first, but days after he starts to drink wine and have fun. This causes delirium symptoms. He gets out of bed and falls from the city walls, causing him to immediately die.

The pathological process that Sinuhe fictitiously managed was probably a convexity meningioma, which can cause symptoms with a long evolution such as epileptic seizures and headaches, although the noise inside the head is more difficult to explain. The physical examination of the skull can show local pain when pressing or tapping it, although imaging techniques make current diagnosis. A symptomatic convexity meningioma is a clear evidence for neurosurgical treatment by performing a craniotomy focused on the lesion and removing the tumour and its dural adhesion as widely as possible. The dura mater is repaired with a biological or synthetic graft. When the tumour infiltrates the bone, the resection thereof can be accompanied by the simultaneous removal of the dural tumour when the adjacent dura mater is torn. In this case the bone is normally discarded and a cranioplasty is performed. In the description of the surgical intervention carried out by Sinuhe, Mika Waltari makes no reference to any action on the dura mater. There are no references to it in any other intervention described in the novel either. Primitive civilisations and those ones involved in the historical period that is covered in this chapter did not voluntarily open the dura mater, save for exceptional circumstances. The tumour had to infiltrate the bone; otherwise there was no reason for discarding the bone and placing a silver plate. For this reason, an alternative hypothesis to the meningioma could be a cranial dural metastasis, which can cause similar symptoms. It affects the bone, which is why it is always sensitive; it covers the dura mater and pierces it, so it could be inadvertently torn when lifting the bone; and, finally, it can infiltrate the brain. This can explain the profuse bleeding that forced Sinuhe to cauterise the adherences of the tumour to the brain.

The surgical procedure described by Mika Waltari has a lot of steps and procedures not described in Greco-Roman's nor in Medieval's trepanations (intradural practice, tumour removal, cranioplasty, use of anaesthetics) and lacks a sort of routine manoeuvres used in Greco-Roman's and Medieval's trepanations (complete procedure done in a single time, suturing the skin). However, some other procedures have the flavour of the Greco-Roman trepanations.

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Part IV

Dark Times. Trepanation in the Middle Ages

De terebris, modiolis, phacotis, scalpris, cycliscis, meningophilacis, ac aliis instrumentis ad cranii perforationes opportunis

Giovanni Andrea della Croce (c1515–1575)

10 Cranial Trepanation During the Middle Ages

Historically speaking, in this chapter we cover the chronological period of the Christian and Islamic Middle Ages. It is generally accepted that the Middle Ages lasted from the fifth century, with the fall of the Western Roman Empire in the year 476 against the European barbarian invaders when the last Roman emperor was deposed, to the end of the fourteenth century or the beginning of the fifteenth century. This is a long period of time of around 1000 years that was full of historic events, such as the advent of the Islamic Empire with its golden age from the eighth century to the fourteenth century, the spread of the printed books in Europe or the discovery of America in 1492. We arbitrarily end the span period of this chapter with the first medical text press printed in the European Renaissance in the middle of the fifteenth century. Although this part of the history of cranial opening was started in Greece in the fourth century BC as we have shown before, it later expanded geographically in the Greco-Roman period. These primeval elements of trepanation, along with a myriad of other cultural, social, legal, political, scientific and knowledge-related aspects, spread from Greece to the whole Mediterranean region and subsequently to mainland Europe, creating thus the essential core of our cultural heritage.

The Islamic and Christian medieval period does not offer technical or medical innovations of greater relevance concerning cranial trepanation [1–6]. Both cultures followed almost without any innovation the Greco-Roman doctrine on trepanation and general management of head wounds and injuries. The fundamentals were in both cases the Hippocratic and Galen writings because Celsus' works were lost until the fifteenth century when they were found, known, translated and published. The temporary evolution of the medical and surgical knowledge between Islamic and Christian cultures is otherwise very different due to a great number of social, economic, cultural and religious features.

10.1 Medieval Islamic Period

Islamic medicine appeared almost out of nowhere by assimilating Hellenistic medicine and reached its greatest splendour in the Al-Andalus (Spain). However, these Islamic physicians only acted as guardians of the previous Greco-Roman knowledge with minor original contributions when dealing about the trepanation. While it had a shining start, the medieval Islamic medicine collapsed in the thirteenth century. In this Islamic world we must highlight Albucasis (Abul Qasim Al-Zahravi, 936–1013), who was born in Al Zahra'a near Córdoba (Spain) and described the trepanation and the instruments used following Hippocrates and Galen's ideas. In his text *'Al-Tasrif'* he points out that most depressed fractures require trepanation as well as some linear fractures but the surgeon who aims to solve

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all wounds of the head with the trepan is *'an idiot or a fool'*. The general technique described by the Islamic authors, including the contemporary Persian author Avicenna (Ibn Sina, 980–1037), consists of just translating into Arabic the Hippocratic texts that were rewritten in Greek by the Byzantine physicians. Their fundamental importance lies in the fact that the Medical Schools of Salerno and Montpellier, where they were translated in turn into Latin, used them afterwards. Something similar happened with Haly Abbas (Ali bin Abbas Majusi Arrajani, 930?–994), a Persian physician whose work is basically the result of translating and incorporating ancient Greek and Indian texts and transcribing ancient Arabic texts [7]. All these authors and their ideas are known in the Christian Middle Ages due to the translation into Latin of their works during the eleventh and twelfth centuries by the Medical Schools of Salerno and Montpellier. Their works also experienced in turn frequent translations and subsequent versions and they were cited, recognised and studied throughout Europe until the eighteenth century.

Victor Escribano-García (1870–1960) described the general procedure and the instruments that were supposedly used by the Islamic physicians and surgeons according to their writings [8]. According to Albucasis the treatment procedure of the injuries of the head and skull, in general terms, started by shaving, making an X-shaped incision and exposing the skull, followed by haemostasis with ointments, refilling and compression of the margins with a tight bandage for 1 or 2 days. After that, the wound was opened again to carry out the trepanation itself. The instruments that were supposedly used were trepans, retractors, lifters, periosteal elevators, dissectors, tweezers, probes and iron-cutting knives. The largest cranial openings were achieved by performing successive holes. The remaining bone was resected with a lenticular knife. He described a trepan that could not dip in the skull, i.e. it would have a system similar to *'abaptista'*. The lenticular is described as an instrument with the shape of a 'triangular knife with a pointed vertex' and that 'had a circular stop to avoid dipping it in the encephalic mass'. No references were made to the use of drillers with a circular crown similar to the *'modiolus'*.

10.2 Medieval Christian Period

Among Christian societies surgical procedures were supposedly irrelevant as they had reservations about these types of treatment, even in the case of war wounds, and due to the general regression in any intellectual or technical activity that was characteristic of the Middle Ages after the collapse of the Roman Empire. During the long period of time that comprises the several centuries from the fall of the Roman Empire until the dawn of the Renaissance, Hippocrates and Galen's doctrines preponderated in the medicine of mainland Europe. However, the original texts could not be studied by the physicians throughout this long period of time, either because they had disappeared, because the existing ones were abandoned in the libraries of the monasteries or because those writings that were available could not be read as they were written in Greek, a language that had been forgotten and almost nobody was able to understand. The first manuscript translations into Latin of the Greek texts were made from the eleventh and twelfth centuries on. In some cases, they were based on the Arabic translations. Latin was an international and highbrow language that physicians (not surgeons) understood at that time. In this matter, Jewish physicians had a strategic advantage as they had direct access to Arabic writings because both cultures geographically coexisted.

Once the problem of getting the information back was solved, the next obstacle to be faced was its dissemination. At that time, before the printing press was routinely used, the original medical texts were handwritten or printed in short runs in Latin with alternative techniques, such as woodblock printing. Many of these original writings were lost and we know about their existence due to the translations or subsequent printings, which introduced changes, explanations and supposed improvements. With every conceivable limitation it seems impressing how much knowledge the authors of the medical texts had about all what had been published until then. Hence, Guy de Chauliac (c1300–1368), a French surgeon who published in 1363 the book *'Chirurgia Magna'*, cites more than a 100 authors and makes around 3300 references to them. In the same way, Henri de Mondeville (c1260–1317) cites 59 authors and makes 1308 citations in his book on surgery titled *'Chirurgia'* [9, 10].

Regarding the illustrations of the surgical instruments, they were missing or unusual in these original writings. The subsequent copies or printouts introduced figures. However, these drawings were more often illustrations that interpret what the original texts gathered according to the knowledge of the copyist and of that time when they were copied. The edited or copied text contained in turn language uses and expressions that were different to the ones used by the original author. In the same way, the instruments shown in the prints were not copies of those drawn by the original authors (if did it), but subsequent designs made by the copyists, translators or editors. As a consequence, nowadays many prints of surgical instruments are frequently mistaken, as they are attributed to authors that never drew them. Therefore, they lack any historical rigour. However, these drawings do have a great historiographical value as they probably represent how the instruments actually were in the historical moment in which the book was copied or printed. This can be clearly checked when consulting the large book collections, in which we can often find several printed editions of lost manuscripts with different timelines and where the drawings of the instruments that were initially described change depending on the date of publication of the different editions. At that time, there were no illustrations concerning anatomy, pathology, lesions and especially surgical techniques yet.

As we have mentioned, the situation of medicine throughout the Christian European Middle Ages from the fifth until the twelfth century was discouraging. The Greco-Roman medical texts stayed out of reach of physicians and surgeons. Consequently, medicine regressed and went back to the healers with an empirical or a magical point of view or was confined to priests and monks in monasteries. Whenever it was practised in a more formal way, they followed to the letter the Hippocratic principles. It is said that in order to heal head fractures monks required an amount of money that was proportional to the number of pieces of bone that they removed and depending on the sound they made when dropping them into a pot. We have discussed in the previous chapter an example of this situation in the work of Paulus Aegineta (625?–690?), a Byzantine physician who recommends treating cranial wounds and fractures by blindly trusting what was suggested by the ancient authors a 1000 years before [11]. Anyway, trepanation was probably a very uncommon practice as cranial wounds and fractures were routinely treated with pastes, poultices, dressings and bandages.

All this changed when the medical schools appeared from year 1000 on, such as the one founded in Salerno. They obtained the Hippocratic knowledge from the Islamic texts, which they translated into Latin, updated and criticised. In their writings there are suggestions about a better handling of the wounds, as well as conceptual modifications on the meaning of pus and some contributions on drugs for analgesia and sedation during the interventions. Trepanation is rejected in different medical texts due to its inefficiency or its danger. Generally, they recommended treating cranial fractures with ointments and cleaning and dressing procedures. However, other texts mention the trepanation and make diagnostic or indication recommendations, although no relevant contributions were made.

Roger of Salerno (c1170–) wrote in 1180 his work *'Practica chirurgiae'*, also known as *'Chirurgiae magistri Rogerii'*, which was updated in 1250 in a new edition by one of his main pupils, Roland of Parma, in Bologna. This book, which was written in a case discussion format to train the students, describes cranial traumas and their handling. It refers to those situations in which patients have suffered a trauma in the head but have no external wound and stresses the fact that they can be associated with fractures. In case of blows or violent impacts with heavy objects the physician must suspect that there is a fracture and open an exploratory incision and trepan. As for depressed fractures, trepan whenever it is necessary to lift fragments. The dura mater must be left intact. Following Hippocrates' ideas, trepanation must not be performed on sutures, eyebrows or areas covered by muscles. He defines those situations with a mortal prognosis: if there is fever, sensitivity-processing disorders or palsy in the arms or legs. Trepanations in cold environments or climates must be avoided. This is why the room must be warmed up with braziers or fire. Roger describes in his book a technique to identify whether the dura mater has been broken during the trepanation process by asking the patients to hold their breaths and observing if liquid or bubbles come out from the broken dura mater, i.e. doing a Valsalva manoeuvre. He also describes a manoeuvre to know if there are linear fractures that are not very visible. In order to do so he asks the patient to break a hazelnut with their teeth to check if there is any pain. Once the scalp has been opened, he uses the ink method described by Hippocrates. Finally, some remarks are made concerning the surgeon, suggesting washing the hands, having an adequate diet, breathing non-corrupted air and some moral advices.

Other Italian surgeons made additional contributions. William of Saliceto (c1210–) describes the treatment of head wounds in 3 days. The first one is for preparing the patient, including the bloodletting; the second one is when the incision on the skin is made; and the third one is when the wound is examined and scrapped in case there is a fracture and the fragments are lifted and removed whenever it is possible. If the fragment is larger than the fracture stroke it is removed by trepanning. Guido Lanfranchi (c1250–1306), founder of the School of Surgery in Paris and author of the book *'Chirurgia magna',* recommends performing trepanations (which are always dangerous) from the beginning but only in case of overlapped fractures or when the dura mater is injured, to remove both bone fragments and humours that press against the dura mater. He suggests diagnosing the fracture by tapping the skull. Teodorico of Cervia (1205–1298) stands up for clean surgery, without admitting the positive effect of the Galenic *'laudable pus'*. Guido da Vigevano (c1280–1349) was an Italian erudite, inventor and physician from Lombardy who wrote in 1345 a book titled *'Anathomia Disegnata per Figures'*, which included 24 anatomical prints, of which 18 have been lost. Several prints focused on neuroanatomy and the eleventh print showed a trepanation of almost the whole cranial vault carried out with the chisel and the mallet [12]. This figure has been used very often to wrongly illustrate how the cranial trepanation was done in the Middle Ages. The simple observation of the drawing suggests that rather than a medical practice it was a cranial resection for the anatomical study of the meninges and the brain.

One of the leading figures of French surgery of that time was Guy de Chauliac (c1300–1368), who was trained in Paris, Montpellier and Bologna and wrote in 1363 a monumental book titled *'Chirurgia Magna'*. The ideas included in his work were considered as a reference for decades. However, his contributions were not abundant and significant. We have consulted the translation into modern French of this work, which was carried out by Edouard Nicaise (1836–1896) and published at the end of the nineteenth century [9]. The translator includes also a great amount of comment and additional information that let us get some idea of the medical and surgical activity in France, particularly in Montpellier, during the Middle Ages. According to Guy de Chauliac there are eight precepts related to trepanation: trepanation will never be carried out on a very weakened patient; the patient will be informed about the dangers thereof; sutures will be avoided; the intervention will not be carried out during the full moon; the trepanation opening will be made in the most declining area so that the pus can be evacuated more easily; in fissures only the required amount of bone will be removed to allow the evacuation of secretions; the pieces that are easily removable will be left so that they are naturally eliminated afterwards; and finally the surgery must be made when opportune. As for the instruments needed, he says that only six instruments are required although it is necessary to have a set of three of each type. The instruments are a trepan to drill the holes (a Parisian model thereof is, according to its description, similar to the *'modiolus'* and the Bolognese model one, similar to the drill or *'terebra'*), retractors, lifters, scrappers (*'rugines'*) to widen fissures, lenticular and finally lead hammer.

These instruments for trepanation attributed to Guy de Chauliac, regardless of their authenticity, are depicted and described by Laurent Joubert (1529–1582) in his book *'Annotations de M. Laurens Joubert, sur toute la Chirurgie de M. Guy de Chauliac'* published in 1578. The book consists of a series of comments by the author to the complete work *'Chirurgia Magna'* by Guy de Chauliac more than 200 years earlier, and we have studied a later edition of the book [13]. The last chapter refers to the *'Interpretation des dictions chirurgicales'*, with a review of surgical instruments. In the book by Joubert, it is recognised that these instruments have been copied from the work of Paré and drawn in turn by Isaac Joubert, son of the author. It is evident that many of these drawn instruments could never be used by Guy de Chauliac, since some of them had not been described in his time. This is the case of the three-legged elevator, which was first described by Von Gersdorf's in 1517. Much later in 1890, Nicaise published some commentaries on the work of Guy de Chauliac and drew on a sheet some of Guy de Chauliac's instruments and no three-legged elevator appears.

Another medical celebrity of that time was Henri de Mondeville (c1260–1317) who was a leading figure of French surgery and surgeon the King Philip IV of France. In 1306 he started his greatest work on surgery titled *'Chirurgia'*, which was handwritten and in Latin, but he could not finish it before his death. We have consulted for this study the translation into French of this work, which was carried out also by Edouard Nicaise (1836–1896) [10]. Along with the translation Nicaise's work contains again a great amount of additional information that let us get a vivid idea of the surgical activity in France, particularly in Paris, during the fourteenth century. The third and fourth chapters of the book by Henri de Mondeville address cranial fractures with and without wounds on the head, respectively. The fifth chapter of the book is about the *'Manière d'opérer manuellement avec des instruments de fer dans la fracture du crâne, lorsque, pour quelque cause, le traitement de Théodoric ou le nôtre ne suffit pas au but que l'on propose'* (How to operate manually with iron instruments in the fracture of the skull, when, for some reason, the treatment of Theodoric or ours is not enough for the purpose that is proposed), which describes in a very detailed way the instruments and the techniques for trepanation. Nicaise states that Henri de Mondeville included a great number of illustrations of his surgical instruments in his original text. However, the translator points out that Henri de Mondeville's most ancient texts that were consulted by him showed only four of the original illustrations. Coincidentally, these images corresponded to instruments related to trepanation, as the rest had been lost in the successive copies because the copyists did not redraw them.

For Henri de Mondeville there were only four instruments required for trepanation, in particular the *'rugine'*, which was a sort of hook that carpenters used to make grooves in wooden beams; the *'trépan'*, which had a cutting edge in both sides or was lanceted and drilled the skull by rotating it with the hand; the *'lenticulaire'*, which was a solid square knife with a lentil-shaped appendage on its tip to avoid cutting the dura mater; and finally the *'élévatoire'*, which was a dissector with a wide end. He suggests that the instruments should be of different sizes and the trepan must have holes on its shank to place a bolt that can be used as a stop so that it cannot dip in the patient's skull. Nicaise includes some plates with his own drawings of the surgical instruments that were used in the Middle Ages and designed according to the descriptions of Henri de Mondeville and other studies. Concerning instruments for perforation, Nicaise includes in these prints the *'trépan des Parisiens, à cheville'* and the *'trépan à Bolonais, à lance'*. The first one is an instrument ended in a screw with some transverse pins or bolts crossing the tip, probably to adjust the depth of the perforation. The second one is a borer with a simple polygonal tip design mounted in a T-handle, like the antique *'terebra'*.

In general, Henri de Mondeville does not recommend surgery in case of closed or linear fractures. When a fracture with loss of substance must be lifted, this will be done with the fingernails whenever it is possible, or with tweezers or a hook. If it is necessary, he recommends performing as many drills as required. They must be close to each other to join them together with a chisel or a hook. Now the fragment of the bone that needs to be removed can be lifted, by levering it with an elevator that is placed beneath it. The dura mater must always be respected. He highlights the fact that the trepanation is a very difficult and delicate intervention, in which the surgeon becomes fatigued and the patient suffers. Trepanations to lift bone fragments can be achieved by two ways. The first one is with the '*rugine*' by making an increasingly deeper groove, which is tiring and bothering, or alternatively with the '*trépan*'. Once the cranium has been drilled, the '*lenticulaire*' is introduced to make sure that the dura mater is kept intact and the bone is cut off, probably by striking with a mallet. The bone is then lifted with the '*élévatoire*'. In another section of the text he also recommends the trepan to remove stuck darts by making a hole on the skull, next to the entry wound thereof.

Apart from all kind of technical details that cover all possibilities of action in an almost obsessive way, the text by Henri de Mondeville is full of general considerations that nowadays would be considered surprising, such as suggesting moving the date of the trepanation forward or delaying it to make it coincide with those times in which dampness in the head is more frequent, such as in the full-moon stage. Another recommendation for those people with head injuries is to avoid sexual intercourses, conversations, society and lustful women, as these actions require a great amount of work from the nervous organs. He also makes some odd recommendations about trepanning in order to frighten those present, to collect more money and to avoid having a bad reputation in case of long treatments or when there are serious complications. The technique used in order to close, clean and dress the wound after the trepanation, which is described in detail, is particularly interesting. Thus, he suggests refilling the imperfection caused by the cranial resection and the scalp wound with compresses made of the best quality fabric that has been soaked in warm wine and wrung, avoiding pressing against the dura mater. This dressing is changed once or twice a day and a powder made of non-corrosive, drying medicines is applied, the composition of which is fully described.

As it happens with the Greco-Roman and Islamic civilisations, the archaeological remains of this long period of time are scarce, as well as the findings of trepanned human remains from the Middle Ages. In the Iberian Peninsula, a location in which the Christian and Islamic cultures coexisted for centuries, Campillo describes four trepanned skulls found in two Spanish necropolises: one was a Late-Roman cemetery from the fourth-fifth centuries and the other one was Islamic [14]. All of the skulls showed no associated pathology that could be identified. López describes two trepanned skulls that were exhumed from a cemetery near Soria (Spain) and dated from the thirteenth and fourteenth centuries [15]. One of them belonged to a man of 50–55 years of age and the other one to a woman of 45–50 years. One of the most relevant cases was the trepanation of the Spanish King Enrique I of Castile, who was still a teenager. Víctor Escribano-García (1870–1960) studied the skull in the middle of the last century [8]. The records of that time unequivocally document that the king was playing in Palencia when he was injured in the head. He died 11 days after, on the 6th of June of 1217. The skull shows a quadrangular trepanation around bregma, which was probably carried out with a chisel and a mallet. A complete description and discussion of this case will be presented as an illustrative case later on. Also, a small number of trepanations have been described in skulls found in burial sites throughout continental Western and Eastern Europe and the British Islands, showing that trepanation was an anecdotal practice but known and widely used.

At that time the trepanations were interventions carried out by trained and qualified surgeons. The organisation of the surgical activity in the medieval period was completely different to the current one. It is interesting to know it in order to understand the real sociocultural environment in which cranial surgery was carried out. The School of Salerno in Italy granted the first medical diplomas in 1140 and the School of Montpellier in France some years after. The School of Salerno had three characteristics that were pretty surprising if we consider the historical moment. It had no religious bonds, it was based on observation and experience and the first syllabus for medical training was designed there. It is even more surprising that they accepted women, although they were specialised in obstetrics and, in general terms, in women's diseases.

Edouard Nicaise (1836–1896), a French surgeon, wrote at the end of the nineteenth century an accurate review of the organisation of medieval surgery in Montpellier and in Paris, and by extension, in the whole France. As we said this review appeared in the introduction and commentaries to Guy de Chauliac and Henri de Mondeville's works [9, 10]. According to Nicaise, we can affirm that there was no general organisation in charge of teaching medicine in France until the thirteenth century. Medicine was a free profession and was regulated differently in each town. Physicians, as other artisans, joined together and were regulated autonomously. Renowned physicians accepted students. Different towns supported this teaching activity and thus the medical schools were founded. They were soon placed under the political city powers or the church's administration. The most relevant examples following this model are the Schools of Salerno or Montpellier. As a final result, universities and their faculties were founded, all of them under the church's control. Papal bulls defined the qualifications granted by the universities such as baccalaureate degrees, bachelor's degrees and master's degrees. Graduates in medicine were called either *'physicus'* or *'medicus'*.

The surgical training and the regulation of the surgical activity were initially out of this organisational model. Hence, in the fourteenth century there was not any university degree for surgeons. The surgical activity was only regulated by the public authorities of towns through evaluation committees that tested the candidates and gave them permission to practise the art of surgery. These surgeons were trained with artisan-like methods by independent masters that gathered in associations but in any event, out of universities and without any syllabus. Barbers and other individuals, such as healers, quacks and swindlers, were out of this more or less regulated world. They successfully carried out certain surgical procedures of that time.

We have a pretty good knowledge of the training that physicians and surgeons received in Montpellier, an important French cultural centre by the Mediterranean Sea during the Middle Ages. In this town the medical training was highly regarded since the twelfth century. At that moment, there was no medical school and each master freely trained their students, who paid them for the teaching. The freedom to teach whatever they wanted was approved in 1180. Due to the increasing number of masters, this practice was regulated and placed under the bishop's jurisdiction in 1220. There was still a model of particular training schools joined together in an association (University of Schools of Medicine) under common regulations. The University of Medicine was the group of the already mentioned private schools and granted baccalaureate degrees, bachelor's degrees and master's degrees under common regulations which included, for example, the books that had to be studied in each of them. However, the degree granted allowed to practise medicine and there was no training on anatomy or surgery. Only in the fourteenth century students were allowed to simulate operations in the corpses of executed prisoners.

Thus, the training on surgery remained outside the university domain and followed the initial model based on particular schools and masters for many decades. At the end of the fifteenth century, in 1490, the School of Medicine of Montpellier established a surgery course for barbers. A lecturer taught this course in Latin and, as barbers did not understand it, the lecturer made commentaries in a mixture of French and Latin afterwards. It was not until year 1595 when the Chair for Surgery and Pharmacy was established in Montpellier, although they continued granting the diploma on medicine at the end of the academic training. Along with surgeons, barbers, whose statutes were established in the middle of the thirteenth century, shared this professional activity.

The School of Medicine of Paris, which was a unification of all masters of medicine, was not founded until year 1634. Again, the surgical activity was completely separated from medicine during the medieval period. The physician indicated the treatments that pharmacists or surgeons later carried out. The physician was a person that should not carry out any manual work and the surgeon was an artisan that does it. In the practice, only a reduced number of physicians practised surgery. In the thirteenth century the surgeons of Paris founded an association or society like other professionals and established their statutes in the *'Livre des métiers'*, which was successively updated. This association was completely independent from the School of Medicine. The association was composed of the same types of members as other professional associations, with the *'Maître'*, the *'Prud'hommes'*, the *'Bacheliers'* and the *'Licenciés'*. An accreditation system to practise surgery was soon established with an exam monitored by the king's surgeons. Such a refinement in surgery caused many routine surgical procedures to go back to barbers' hands. After a short while there were more barbers than surgeons who carried out surgical interventions, including also the bloodlettings, which were characteristic of barbers, and minor procedures such as teeth removal, cupping or treatments for dislocations. Consequently, the role of barbers became more and more important and their presence in society increased. They soon wanted to have their own qualification as barber surgeons. In the sixteenth century each bourgeois had its own barber, to whom they entrusted their health. In the sixteenth century there were *'robe courte'* surgeons or barber surgeons in Paris, who were grouped in the *'Collège de Côme'*, and *'robe longue'* surgeons or authentic surgeons who were qualified for any type of surgery. However, both types were soon admitted in the medical schools.

There are also some modern studies that allow us to know how the training of a surgeon was in Spain in the fifteenth century [16]. One of the first European universities that established a Chair for Surgery was the University of Valencia in 1499. Until then, barber surgeons of that town were grouped in a professional association that created a *'Estudi'* (School) of surgery which was granted a royal privilege that allowed them to carry out dissections of corpses. They established a 5-year compulsory training in order to practise surgery in 1486. Just like in France, there were professionals specialised in specific tasks who treated diseases both in towns and in rural environments as well as people whose activities were focused on beliefs and the empirical world rather than on scientific ideas.

This same situation occurred in England, where the surgeons who were trained in the university gathered in the Fellowship of Surgeons [17]. They had distant relationships with the Company of Barbers, which joined the barber surgeons together. It is likely that these two separate associations already existed since the fourteenth century and controlled the practise of surgery in different fields. In 1354 four surgeons were given the authorisation to recognise the practise of surgery and about a 100 years later this authority was granted to the Barbers Company. However, the Fellowship of Surgeons was in the end the organisation that controlled the training and recognition of both types of surgery professionals at the end of the century with some collaboration from the physicians. All this took place during the kingdom of Enrique II. Between the years 1423 and 1425 there was an attempt to establish a centre and joint training for physicians and surgeons in a single degree but this was unsuccessful in the end.

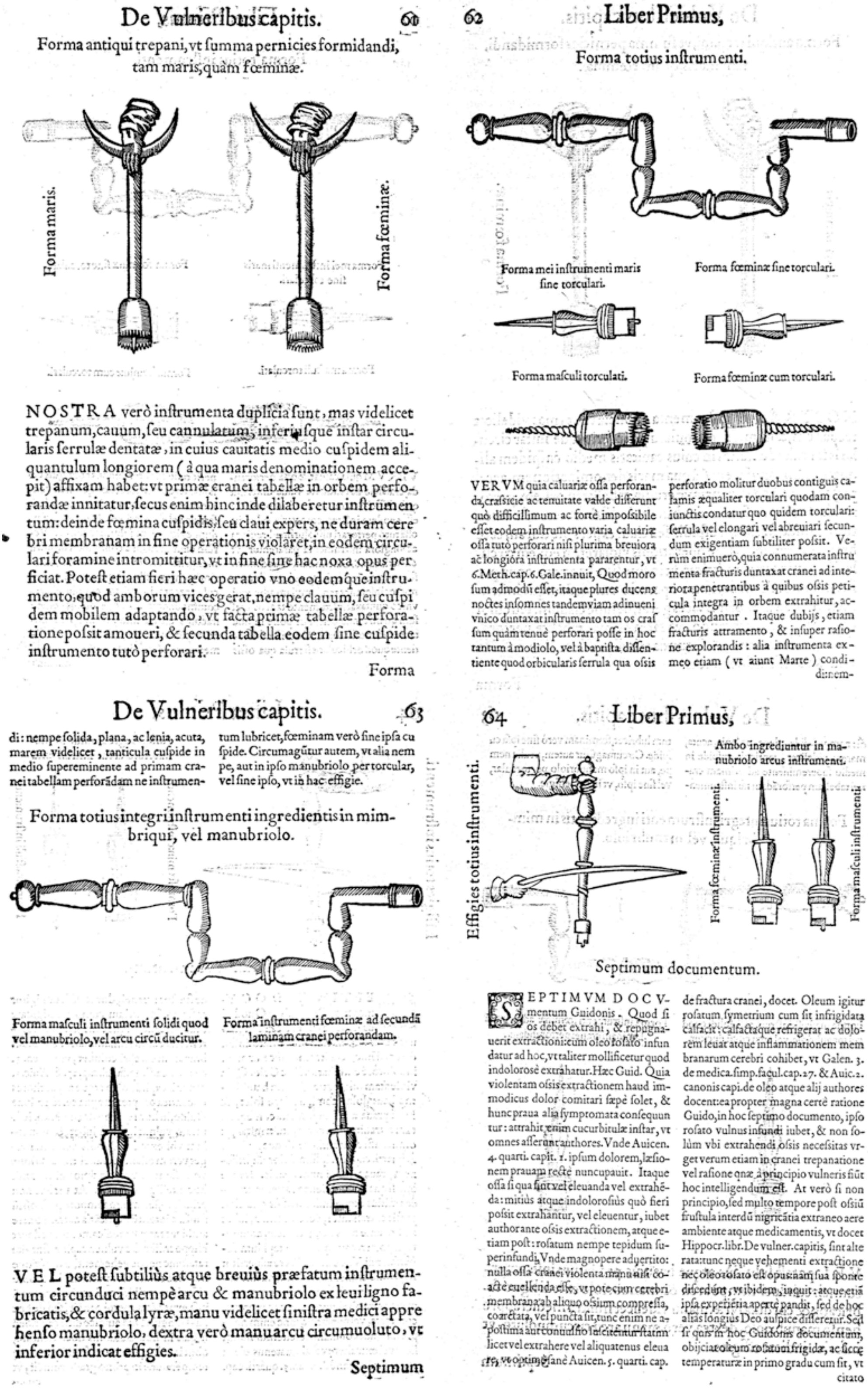
10.3 Interpretation During the Renaissance of the Instruments Used for Cranial Trepanations in the Middle Ages

As it was mentioned, a great amount of the written information and, of course, almost all the iconographic information of the surgical instruments that were used in cranial trepanations during the Greco-Roman period and the Middle Ages come from the first printed medical texts from the fifteenth and sixteenth centuries. In general, these books were encyclopaedic works in which the medical knowledge they had until then was transcribed and gathered and, when applicable, a little amount of new information was added. They also included beautiful illustrations of the surgical instruments. It seems difficult that the author knew all contents, medicines, and instruments described in the treatises and also used them in medical practice. On the other hand, it was very common that authors copied a great amount of text and numerous illustrations from each other. This is why it is sometimes very hard to identify the original author of the writings or the drawings. Finally, it is surprising how quick the re-editions of the treatises or even the translations thereof were done. In this regard, many texts were initially written in Latin, seldom in Greek, and then they were translated into national living languages or soon they were just written in such languages.

The authors from the Renaissance who best described and illustrated the surgical instruments used for trepanations were probably Giovanni Andrea della Croce in Italy, Ambroise Paré in France and Andrés Alcázar in Spain. They published and printed their works during the second half of the sixteenth century and will be discussed in the next chapter. An earlier surgeon who wrote about trepanation and played an important role in the design of instruments for trepanation was Andrés Alcázar (c.1500–1584). Alcázar was born in Guadalajara (Spain) and he was trained as a surgeon in Salamanca, where he will achieve the Chair for Surgery. When he was old, his disciples encouraged him to write in Latin his only work titled *'Chirurgiae libri sex: in quibus multa antiquorum et recentiorum sub obscura loca hactenus non declarata interpretantur'*, published in Salamanca [16, 18].

Alcázar mentions that when he was younger he made trepanning tools that 'had not been seen or known until then' and he showed those instruments to the surgeons who visited him. Luís de Lucena in turn showed these instruments throughout the whole Europe. Lucena was a humanist and physician, friend of Alcázar, who travelled and lived in Italy and France for many years. Alcázar points out in a sort of list of improvements similar to those included in modern patents that his designs enhanced the three disadvantages of the classical instruments: they avoid penetrating the skull, they avoid piercing the dura mater with the central pin and they avoid using both hands to drill. To do so, his designs have a stop mechanism, there is a female instrument without the pin and they are triggered by a winding mechanism or a brace. The first ones are the old trepans, which he generically called *'antique trepani'* and after he includes his own designs. The drilling heads are all cylindrical and hollow and have serrated edges like the old *'modioli'*. Some of them have a central pin (*'forma masculi'*) and others do not have it (*'forma fœminæ'*). The handles have either a T shape or are similar to a carpenter brace. Finally, they can be also straight, mounted on an arch with a rope. The drilling heads are interchangeable within the different handles. It is remarkable that all the drawn instruments show their Latin name in writing above or beside them.

To illustrate his designs, he drew the different drillers in pages 61–64 of his book (Fig. 10.1). Page 61 shows the instruments that Alcázar named 'antique instruments', with the male crown (*'forma maris'*) that has a central pin that slightly protrudes from the cutting crown, and the female crown (*'forma feminae'*) that has no pin. He points out that these drillers are dangerous and he illustrates the handle and explains accurately in the text how to drill. The text in this page and the following ones describes Alcázar's 'own instruments', which are also drawn. In page 62 Alcázar draws above the whole instrument of the trepan with a brace-like handle, the central row shows the non-threaded drillers (*'sine torculari'*) and the lower row shows the threaded drillers ('cum *torculari'*), both males and females. The characteristic highlighted by Alcázar is that his instrument has two crowns: a cutting crown and an external one that is threaded onto the first one and acts as a stop. This way it is possible to accurately adjust the cutting depth



De Vulneribus capitis. 61

Forma antiqui trepani, vt summa pernicies formidandi, tam maris, quàm fœminæ.

Forma maris. Forma fœminæ.

NOSTRA verò instrumenta duplicia sunt, mas videlicet trepanum, cauum, seu cannulatum, inferiusque instar circularis ferrulæ dentatæ, in cuius cauitatis medio cuspidem aliquantulum longiorem (à qua maris denominationem accepit) affixam habet: vt primæ cranei tabellæ in orbem perforandæ innitatur, secus enim hincinde dilaberetur instrumentum: deinde fœmina cuspidis, seu claui expers, ne duram cerebri membranam in fine operationis violaret, in eodem circulari foramine intromittitur, vt in fine sine hac noxa opus perficiat. Potest etiam fieri hæc operatio vno eodemque instrumento, quod amborum vices gerat, nempe clauum, seu cuspidem mobilem adaptando, vt facta primæ tabellæ perforatione possit amoueri, & secunda tabella eodem sine cuspide instrumento tutò perforari.

Forma

62 Liber Primus,

Forma totius instrumenti.

Forma mei instrumenti maris sine torculari.

Forma fœminæ sine torculari.

Forma masculi torculati.

Forma fœminæ cum torculari.

VERVM quia caluariæ ossa perforanda, crassicie ac tenuitate valde differunt quò difficillimum ac fortè impossibile esset eodem instrumento varia caluariæ ossa tutò perforari nisi plurima breuiora ac longiora instrumenta pararentur, vt 6. Meth. cap. 6. Gale. innuit, Quod moro sum admodũ esset, itaque plures ducens noctes insomnes tandem viam adinueni vnico duntaxat instrumento tam os crassum quàm tenuè perforari posse in hoc tantum à modiolo, vel à baptista dissentiente quod orbicularis ferrula qua ossis perforatio molitur duobus contiguis ca- lamis æqualiter torculari quodam coniunctis condatur quo quidem torculari: ferrula vel elongari vel abreuiari secundum exigentiam subtiliter possit. Verùm enimuerò, quia connumerata instrumenta fracturis duntaxat cranei ad interiora penetrantibus à quibus ossis peticula integra in orbem extrahitur, accommodantur. Itaque dubijs, etiam fracturis attramento, & insuper rasione explorandis: alia instrumenta ex meo etiam (vt aiunt Marte) condi- dimem-

De Vulneribus capitis. 63

di: nempe solida, plana, ac lenia, acuta, marem videlicet, tanticula cuspide in medio supereminente ad primam cranei tabellam perforãdam ne instrumentum lubricet, fœminam verò sine ipsa cuspide. Circumagũtur autem, vt alia nempe, aut in ipso manubriolo per torcular, vel sine ipso, vt in hac effigie.

Forma totius integri instrumenti ingredientis in mimbriqui, vel manubriolo.

Forma masculi instrumenti solidi quod vel manubriolo, vel arcu circũ ducitur.

Forma instrumenti fœminæ ad secundã laminam cranei perforandam.

V E L potest subtiliùs atque breuiùs præfatum instrumentum circunduci nempè arcu & manubriolo ex leui ligno fabricatis, & cordula lyræ, manu videlicet sinistra medici apprehenso manubriolo, dextra verò manu arcu circumuoluto, vt inferior indicat effigies.

Septimum

64 Liber Primus,

Effigies totius instrumenti.

Ambo ingrediuntur in manubriolo arcus instrumenti.

Forma fœminæ instrumenti.

Forma masculi instrumenti.

Septimum documentum.

SEPTIMVM DOCVmentum Guidonis. Quod si os debet extrahi, & repugnauerit extractioni: cum oleo rosato infundatur ad hoc, vt taliter mollificetur quod indolorosè extrahatur. Hæc Guid. Quia violentam ossis extractionem haud immodicus dolor comitari sæpè solet, & hunc praua alia symptomata consequuntur: attrahit enim cucurbitulæ instar, vt omnes asserunt authores. Vnde Auicen. 4. quarti. capit. 1. ipsum dolorem, læsionem prauam rectè nuncupauit. Itaque ossa si qua sint vel eleuanda vel extrahẽda: mitiùs atque indolorosiùs quò fieri possit extrahantur, vel eleuentur, iubet author ante ossis extractionem, atque etiam post: rosatum nempe tepidum superinfundi, Vnde magnopere aduertito: nulla ossa cranei violenta manu nisi coactè euellenda esse, vt pote cum cerebri membrana ab aliquo ossium compressa, coarctata, vel puncta sit, tunc enim ne apostima aut conuulsio [illegible] licet vel extrahere vel aliquatenus eleuare, vt optimè sanè Auicen. 5. quarti. cap. de fractura cranei, docet. Oleum igitur rosatum symetrium cum sit infrigidata calfacit: calfactaque refrigerat ac dolorem leuat atque inflammationem membranarum cerebri cohibet, vt Galen. 3. de medica. simp. facul. cap. 27. & Auic. 2. canonis capi. de oleo atque alij authores docent: ea propter magna certè ratione Guido, in hoc septimo documento, ipso rosato vulnus infundi iubet, & non solùm vbi extrahendi ossis necessitas vrget verum etiam in cranei trepanatione vel rasione quæ à principio vulneris fiũt hoc intelligendum est. At verò si non principio, sed multo tempore post ossiũ frustula interdũ nigricãtia extraneo aere ambiente atque medicamentis, vt docet Hippocr. libr. De vulner. capitis, sint alterata: tunc neque vehementi extractione nec oleo rosato est opus: nam sua sponte discedunt, vt ibidem, inquit: atque etiã ipsa experiẽtia apertè pandit, sed de hoc aliàs longius Deo auspice differetur. Sed si quis in hoc Guidonis documentum, obijciat oleum rosatum frigidæ, ac siccę temperaturæ in primo gradu cum sit, vt citato

Fig. 10.1 Instruments related to the trepanation by Andrés Alcázar (Alcázar, A. Chirurgiae libri sex: In quibus multa antiquorum et recentiorum sub obscura loca hactenus non declarata. Salamanca; 1575) and a whole disc of bone is removed. He points out that the hole can be made with a single crown, but in this case the pin must be mobile in order to remove it once the outer table has been drilled. Page 63 represents above the whole instrument with a brace-like handle. He repeats below two of the drawings that appeared on the previous page, emphasising now that the female crown is used to perforate the inner layer of the skull (*'secundi laminam cranei perforandam'*). Finally, in page 64 Alcázar shows the drilling handle with an arch. Both of them are made of wood. It works with an arch and a guitar string and as it is represented by the illustration. Two non-threaded drillers that can be inserted onto the handle are shown beside.

Alcázar can be considered as a transitional surgeon who probably used primitive instruments, which he generically calls 'antique', during his first years of medical practice. With the aim of solving the problems and shortages of these instruments, he later states that he has invented and made a new generation of trepanning instruments, referred to as 'own instruments'. These instruments were those, which, as he affirms, he proudly showed to other surgeons. His work, which was written at the end of his life, describes and includes the drawings of both antique instruments and his own. Although the author is pleased with these new designs, they are actually simple modifications of the old instruments. Many other authors also showed an interest in claiming the described designs as their own, as at that time there were no patents or copyright. When these designs are studied in detail, it can be observed that they are not only very similar but sometimes exactly the same.

The Hippocratic and Greco-Roman writings describe accurately the techniques and the instruments needed for cranial trepanations. It is amazing how these contents were copied and translated for almost 2000 years without considerable modifications until the Renaissance. These vicissitudes are the same as the ones that have influenced many other medical or surgical aspects. Once the Middle Ages, a dark period of time concerning almost all the knowledge and technologies in Christian societies, were over such knowledge was recovered and gathered initially by the medical schools and later during the early Renaissance. At that time, there was an opportunity to enhance all these surgical techniques and technology, which was done for centuries afterwards. This development will be tracked along the following chapters.

10.4 Illustrative Case

At that time there were no case reports in the medical texts to be discussed and the historical documents are scarce. We include in this section the well-studied case of the trepanation carried out to treat a head injury suffered by the young king Enrique I of Castile (Spain) in the thirteenth century [8, 19].

10.4.1 Enrique I of Castile's Head Injury

We present the case of Enrique I of Castile (Spain), who underwent a trepanation after suffering from a cranial trauma. Enrique I was the king of Castile since the age of 10 and Ms. Berenguela ruled as regent in a complex environment full of intrigue and familiar interests regarding inheritance that was characteristic of that time. At that time, the court was settled in Palencia and King Enrique I, who was 13 years old, was living at the house of the town's bishop, Mr. Tello Téllez de Meneses. By chance he suffered a fatal accident there, which was duly noted in the records of that time. The *'Anales Toledanos Primeros'* (Historical Annals of Toledo) relate it as follows: *'En Palencia el rey don Enric trebellaba con sus mozos e firiólo un mozo con una piedra en la cabeza, non por su grado, e murió ende VI días de junio, en dia de martes, era MCCXVII'* (King Enrique was playing with his attendants in Palencia and one of them unintentionally hurt him in the head. He finally died on Tuesday the 6th of June of 1217). It was recorded in a similar way in the *'Crónica de los Veynte Reyes'* (Chronicle of the Twenty Kings): *'En Palencia, andando trebellando con sus donceles, un doncel de los del linaje de los Mendoça, tiró un tejuelo, e dio con él en el tejado, e derribó una teja, e dio* *al rrey en la cabeça tan gran ferida que fizol caer en tierra e después vivió onze días e murió dello'* (He was playing with his pages in Palencia when a page who belonged to the Mendoça line of descent threw a piece of tile which hit the roof and dropped a tile. This tile hurt the king so hard in the head that made him fall to the ground and he then lived eleven days and died of it). The data of this trepanation are explained in detail in the study carried out by Víctor Escribano-García (1870–1960), a Professor of Anatomy from Burgos (Spain) who exhumed his remains in 1948 and published later a monograph about it. The skull shows a quadrangular surgical trepanation with a side of about 3.5 cm. The margins are neat and perpendicular, as if a cutting instrument had made them with a sharp edge. The internal table in one of the margins protrudes a bit from the section edges, probably as a consequence of a levering action. The osseous resection is located to the right of the parasagittal plane. The middle line exactly crosses bregma. The cranial fragment was not found inside the king's grave. No signs of fracture are evidenced on the rest of the skull. Incidentally the skull has a persistent metopic suture. The hypothesis formulated after the study by Escribano-García concludes that the king suffered a stellate fracture that was completely enclosed by the trepanation, which was carried out with a cutting instrument, probably a chisel, and never with drilling instruments. Experts venture to say that it was performed in two stages.

The injury was unequivocally caused by a direct impact with a small projectile at medium speed. The game that the king was playing could be a sort of lawn game known in Spanish as *'tejo'*, *'tejuelo'*, *'chita'* or *'tuta'*. The aim of the game is knocking over a vertical stick with a piece of tile (called *'teja'* in Spanish). The artefacts to be thrown were initially pieces of tile but later some iron round pieces were also used. This is why the game is dangerous if certain rules concerning the positioning outside the throwing area are not respected. Therefore, we must deduce that king Enrique was wounded to death with a piece of tile, that could be ceramic or metallic, in a fatal and unexpected accident of the game, or that the piece of tile could have removed a tile from the roof that hit the king. Some records recount that those responsible for the assassination were identified and subsequently imprisoned and extrajudicially executed.

A direct impact on the skull could have caused an open depressed fracture circumscribed by the trepanation location, i.e. to the right of the parasagittal plane, as there are no fracture lines on the skull. Considering the available information, it is difficult to explain the death of the king as a consequence of the initial trauma 11 days after it. Unfortunately, we have no information about the treatment the king underwent and, in fact, the trepanation was not included in the records. This is why it is not possible to know either when it was carried out since the moment of the trauma. According to the medical practice of that time, an open cranial fracture was a formal indication to be trepanned. The supposed fracture, regardless of its type, was completely surrounded and removed during the trepanation following the recommendations of that time. This is why we cannot determine its nature, as the osseous resection piece was not recovered. The trepanation was probably carried out with a chisel and it was completed with a saw. The trepanation was technically adequate, although the middle line crossed bregma and thus there was a possible risk of injuring the sagittal sinus.

All the previous information let us venture that the trepanation was correctly recommended, considering the knowledge of that time. Removing the fracture, if present, was technically correct but a possible lesion of the sagittal sinus could have been deadly, either by causing an uncontrollable acute blood loss or, in case it was stopped by packing, by causing a thrombosis with a secondary cerebral venous infarction which was contributed by the anaemia and dehydration. Alternatively, the death could have been caused by an infection of the wound and sepsis or by complications related to other treatment methods that were applied.

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Part V

Lights and Shadows. Trepanation and Trephine in Modern European Cultures

Quel effect avantageux a-t-on pu obtener de ce procédé presque barbare?

Jean-Pierre Gama (1772–1861)

L'operation du trépan n'est point mortelle par elle-même

Jean-Louis Petit (1674–1750)

11 Surgical Instruments for Trepanation and Trephine in Modern Age

The Modern Age corresponds with the historical period that followed in Europe the Renaissance, until the end of the nineteenth century or beginning of the twentieth century. This era includes the movement of the Enlightenment in the eighteenth century, when the sciences in general and the medical and surgical understanding flourished thanks to the rationalism applied to all the fields of the knowledge.

However, only a handful of small advances along with constant reinventions of surgical instruments for trepanation appeared in the historical period that we are now tracing, rather than revolutionary changes concerning the concept or the surgical technique. In order to classify the tools used for making a cranial opening we are going to distinguish among the basic instruments for cranial drilling, lifting instruments for bone fragments and other instruments required for the intervention. Drillers were used when it was necessary to perforate the skull. When the skull was fractured, fragments could be removed with bone forceps or tweezers and bone fragments were elevated with lifters. The chisel and the mallet were normally used to enlarge the osseous window. Luckily, there is a great amount of written evidence of the designs in the descriptions and illustrations included in the medical texts and catalogues later on. Many original surgical instruments can be found in collections and museums.

The writings from the Renaissance showed in a more or less idealised way the surgical instruments described in the text at first. Sometimes they used very clumsy and basic drawings. However, they soon included beautiful illustrations that reflected the real instruments more faithfully. These illustrations were later gathered in prints that were separated from the text as the printing process of that time did not allow inserting the images between the paragraphs. The captions or explanations about the prints were included in the text or in separate sheets. These prints might appear in between the pages of the volume or together at the end of the work. The first catalogues of surgical material appeared later, during the seventeenth and eighteenth centuries. All of this iconographic information gives us a good idea about the instruments used for cranial trepanations. Many of those drawings and prints are shown in this book. They have been taken from medical texts written by the most relevant authors concerning trepanations, which are publicly available as public domain books.

Surgical instruments were made of metal for centuries. However, the handles and some accessories were made of very different materials. Metals, such as iron or steel, were not very resistant to corrosion, which was caused by the water or soap used for cleaning them. For this reason, some parts were made of gold or silver. Manufacturers started using galvanised or stainless steel in France in 1840 and in the United States later. This increased the durability of surgical materials. Other materials used in instruments,

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particularly in the handles, were ebony or mahogany wood, bone, horn, tortoise shell, whalebone, resin or composite. Porous materials were quickly substituted after the adoption of aseptic and antiseptic techniques, as they did not grant the sterilisation. We can affirm that all surgical instruments were completely made of stainless steel from 1880, even the handle. This change appeared in the United States later, around the end of the century. We can also assume that old instruments were still used for many years, particularly in war surgery or in private outpatient activities.

Only a few medical texts include references about the manufacturing methods or the maintenance of the instruments and how they were known or acquired by the surgeons. In general terms, surgeons ordered to manufacture their own instruments in foundries and smithies and they later showed them to their colleagues. As a consequence, many workshops that were specialised in manufacturing surgical instruments appeared and started selling these designs to other surgeons. The designs were made known by means of the catalogues. Some medical texts already included several pages at the end that showed the instruments with an evident advertising purpose since the seventeenth century. The study of catalogues is a great historiography source.

Surgeons cared about the quality and the maintenance of the surgical instruments, as it can be observed in some remarks. John Woodall (1570–1643) wrote in his book '*The Surgions Mate',* which was published in 1617, that the first thing the surgeon must do when trepanning is to be sure that the instrument is in good condition and that its manufacturing has been optimal (*'the best making'*), that it is dust-free and perfect, without faults. He then specifically wrote that *'of those brought from Germany are not to be used; not yet to be tolerated'*, which gives us a good idea about the fact that these surgical items became trading commodities from afar [1]. However, his personal opinion about German manufacturing was not particularly positive. Woodall listed the surgical instruments and stock of drugs that must be kept inside the chest of a navy surgeon (Fig. 11.1).

The list of surgical instruments used in trepanations has no end. The different surgical schools and authors have suggested individual solutions and innovations concerning the cranial drilling systems over the centuries. Many authors criti-

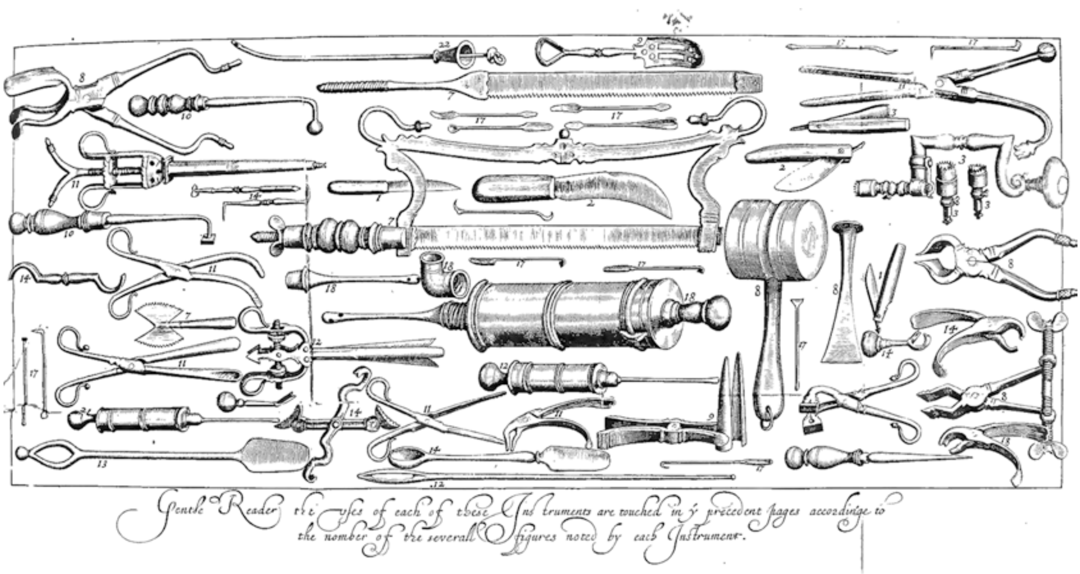

Fig. 11.1 Surgical instruments to be contained in the chest of the naval surgeons as drawn by John Woodall. Among the instruments are the brace trepan (3), the skull saw (7) and the hammer and the chisel (8) (Woodall J. The Surgions Mate. London: Edward Griffin; 1617)

cised this wide variety of instruments. They highlighted the importance of reducing the number of instruments required for trepanation, making the technique easier. Many of these innovations did not flourish because of the factors that influence the final selection of the instruments. These include not only their own value in surgery, but also the importance of traditions, surgical schools and the industry as well as the opposition by professionals when it came to adopting changes and new technologies.

We are going to review and show the instruments related to cranial opening and their historical evolution from the Middle Ages until the end of the nineteenth century. All the instruments of cranial surgery and trepanation that we will describe next are collected in the figures embedded in the following chapters, because figures in this book are organised following the authors and texts from where they were collected and not on the type of instruments. Some authors gather particularly exhaustive collections of surgical instruments representative of the time. In the sixteenth century, we highlight von Gersdorff, Berengario, Paré, Della Croce and Guillemeau; in the seventeenth century Woodall and Scultetus; in the eighteenth century Garengot, Heister and Lesne; and, finally, in the nineteenth century Benjamin Bell and Bourgery.

11.1 Instruments for Drilling the Skull

Nearly all the instruments used for drilling the skull have mainly been modifications of the pointed drillers that were similar to the old *'terebra'* and the circular drillers with serrated edges that were similar to the old *'modiolus'*.

11.1.1 Terebra-Like Drillers

The first type of cranial perforators is the terebra-like drillers (drills, trepans). All type of drills with different sizes and shapes have been manufactured: pointed or blunt, flat with two edges, spherical, countersank or with a truncated cone shape and serrated external surface. They are normally wider on their proximal end to prevent the driller from dipping inside the head when perforating the internal table of the skull. A specific terminology for each type of driller was created over time, including three main different types.

The perforating drill is nothing but a simple pyramid-shaped tip (punch). It only aims to perforate the outer table, sometimes the whole thickness of the skull. The braking system is the pyramid shape of the tip itself. It was used as the first step in trepanations, especially to adapt the central pin (which will be described later) that all crown drillers had afterwards. It was also used in bony sequestra or bone with 'caries', that is, those bones affected by an infectious or neoplastic disease and with a lack of bone consistence. It allowed draining necrotic or purulent accumulations in the bone or located between the bone and the dura mater.

The exfoliating drill aims to perforate the skull bone by making a cylindrical hole, similar to the one made on a barrel to place the spigot. It was generally used to remove only the outer table. In this case, its purpose was to remove the outer table to expose the diploe and the internal table and to confirm or discard bone contusions or fractures of the internal table. Both diagnoses are currently irrelevant but they were important in the medicine of that time. The design of the exfoliating drill has a shank with an enlarged end. Its edges are flat and sharp and it has a small punch on its middle point in order to stabilise it.

Finally, there are drills with a truncated cone shape. They are solid and have a grooved or striated external surface. They were used to advance in the bone-drilling process once it had been started with the punch or the exfoliating drill. It has had a variable size and shape but its use has become more restricted over the centuries. Its aim was to make a complete perforation of the bone by making a small hole. Once the perforation is completed, a certain amount of bone sawdust was obtained. Its truncated cone shape prevented it from dipping inside the head.

11.1.2 Modiolus-Like Drillers

The second type of cranial perforators is the modiolus-like cranial drillers (trephine). The designs of trephines or trephine crowns have always been far more complex than the designs of drills. Trephines had cylindrical heads with different diameters. They also had saw teeth of different sizes on their distal edge; hence they are called crowns. Cylindrical trephines were hollow and had a smooth external surface. The braking system of cylindrical trephines to prevent them from dipping inside the skull once the perforation is over consists of the fixed external rims or external crowns or adjustable caps that serve as blocks. These cylindrical trephines correspond with the old *'modioli'* but this name became erased soon from the medical texts. Other type of trephines had a slight truncated cone-shaped head. These truncated cone-shaped trephines had their larger diameter on their proximal end to prevent them from invading the intracranial space. They were also hollow. The external surface was grooved or striated to allow cutting the bone. The distal edge could also have saw teeth. The braking system is the truncated cone shape of the instrument itself. It was said that cylindrical crowns cut the bone better than those with a truncated cone shape.

All trephines had systematically a central pin that projected a bit from the end of the initial cutting level. It was fixed to the skull as it worked as a fixed rotation axis of the cutting crown to prevent it from sliding. The pin could be placed in a small hole made with a punch in turn. This pin was a sharp metal shank that run inside the vertical shank and which could be removed or retracted in accordance with the surgeon's wishes. It was called *'pyramide'* in French. This mechanism was modified at the end of the eighteenth century. Xavier Bichat (1771–1802) made his own trepan, in which the pyramid was part of the handle's axis [2]. This way, the crown was the element that ran along the pyramid and it was fixed to it by means of a set screw.

The cutting crowns had a variable diameter. Surgeons had different crowns with a different diameter. They could be exchanged at the end of the handle. The larger diameter never exceeded 5 cm. The final result of the perforation with a trephine crown was a perfect circular hole, with (nearly) vertical margins. A disc with the whole thickness of the bone was obtained. In the centre of the external surface of the bone disc it was usually seen the hole made by the pyramid.

The successful final designs were the truncated cone-shaped crowns or perforators. They were used until the end of the nineteenth century although as we are going to explain there were models involving any combination of the described elements over the years. It is surprising that many authors consider that Gabriel A.D. Galt (1830–1908) was the one who presented for the first time a version of the trephine crown in the New York Academy of Medicine in May of 1860. It had a truncated cone shape rather than a cylindrical one (which, according to these authors, was the most used by then). This crown was soon praised and widely used in the United States and in Great Britain. However, although the truncated cone shape has been related to the name of Galt since then, it is patent that these crowns had already been known and used for centuries. This fact was revealed and reported to the pertaining authorities by some surgeons and manufacturers. However, their actions were fruitless in that time.

The cutting crown of the trephine was designed to be able to perforate the whole thickness of the skull and remove a perfect disc with the same thickness than the bone. However, surgeons have been concerned about injuring the dura mater with the trephine teeth since ancient times. For this reason, it was common that surgeons recommended drilling only the outer table and the diploe. A layer of internal table was left intact by checking it visually or using a probe. This layer of bone was partially broken later with the chisel and the mallet. As soon as possible once the internal table was opened, the *'meningophylax'* was placed through a hole to protect the dura mater from de chisel. A late alternative option was to introduce through such hole the *'lenticular'* knife and complete the bone resection then. The result of this type of perforation was two discs: the first one made of the outer table and the diploe and the second one made of the internal table. Surgeons used lifters in order to lift these both discs. A particular instrument called *'tirefonds'* was also invented for this purpose, but we will describe their use in this field later.

11.2 Handles

The drilling instrument, regardless of its type, had to be mounted on a handle so that the surgeon could use it. Drillers were generally interchangeable in the handles. They were mounted onto the distal end of the handles, which allowed a more or less ergonomic use that we are now going to describe. The successful designs of the basic handles onto which the cranial drilling system was mounted had two models: those used with just one hand or borehole-like and those that had to be used with both hands or brace-like (Figs. 11.1 and 11.2). Other systems have had a short life or irrelevant success. They will be discussed but more briefly.

11.2.1 T-Handles

The simplest handles for making a cranial drill needed only one hand (borehole-like handles). These systems had the driller mounted onto the end of a handle with a transverse handgrip (T-handle). It was firmly held with the hand and used by making rotation half circle movements by repetitive pronation-supination. These were combined with an axial pressure applied over a point of the skull until perforating it. The perforating element could be a drill or a trephine. In both cases they could be integrated in the handle or be interchangeable. If they were interchangeable, there was a fastening mechanism to fix them to the vertical shank of the handle that consisted of an embedding system, a screw clip or a pin. T-handles were used during all this period. However, it is interesting to observe how they chose a combination of the T-handle with a truncated cone-shaped trephine driller, which had a wider use in English-speaking countries (particularly in the United States during the American Civil War). Other authors recommended it in order to carry out trepanations when travelling by ship as the oscillating movements of the vessel did not hinder its use.

As we have already mentioned, John Woodall (1570–1643) was attributed the invention of an instrument with a T-handle and a cylindrical drilling crown that could be used with one hand in 1639. He called the instrument *'tribus finibus'* or *'tres fines'*, meaning that it had three tips or edges: two of them forming the T-handle and the other one in the drilling crown. Similar instruments had been previously described and illustrated by Giovanni Andrea della Croce in 1573, Girolamo Fabricius d'Acquapendente in 1617 and others.

The drilling element and the vertical shank were always made of metal in all designs. The horizontal part of the handle or handgrip was initially made of metal. However, it was later manufactured in ivory, bone or hardwood such as ebony or mahogany wood. Finally, they were made of hard rubber or metal again, after the instruments started being sterilised by boiling them. This horizontal part was usually cylindrical and had the adequate diameter so that it could be firmly held with one hand. It used to be symmetric as well. The handle had a ratchet mechanism that facilitated the surgeon's work in later models. However, they were asymmetric in some models, with one side longer than the other one. There is a curious design with curved sides called 'crane wings' which was presented by John Woodall (1570–1643) in the second edition of 1639 of his book *'The Surgions Mate'*, which was published in 1617.

The first edition of the book has only one plate with the complete set of instruments of the chest. In the second edition of 1639 other plates are added, one of them picking up all the instruments for trepanation (Fig. 11.2). There are punch and trephine drills, both cylindrical with braking caps and truncated conical, all with central pin. These pieces are mounted on a horizontal handle of original design in *'crane wings'*. Also are represented bone forceps for fragments, two knives and forceps for extraction of foreign bodies. A drawing presents how to perform a trepanation on a dry skull and the bone disc obtained. Woodall indicates that the instrument 313 *'is a crown saw*

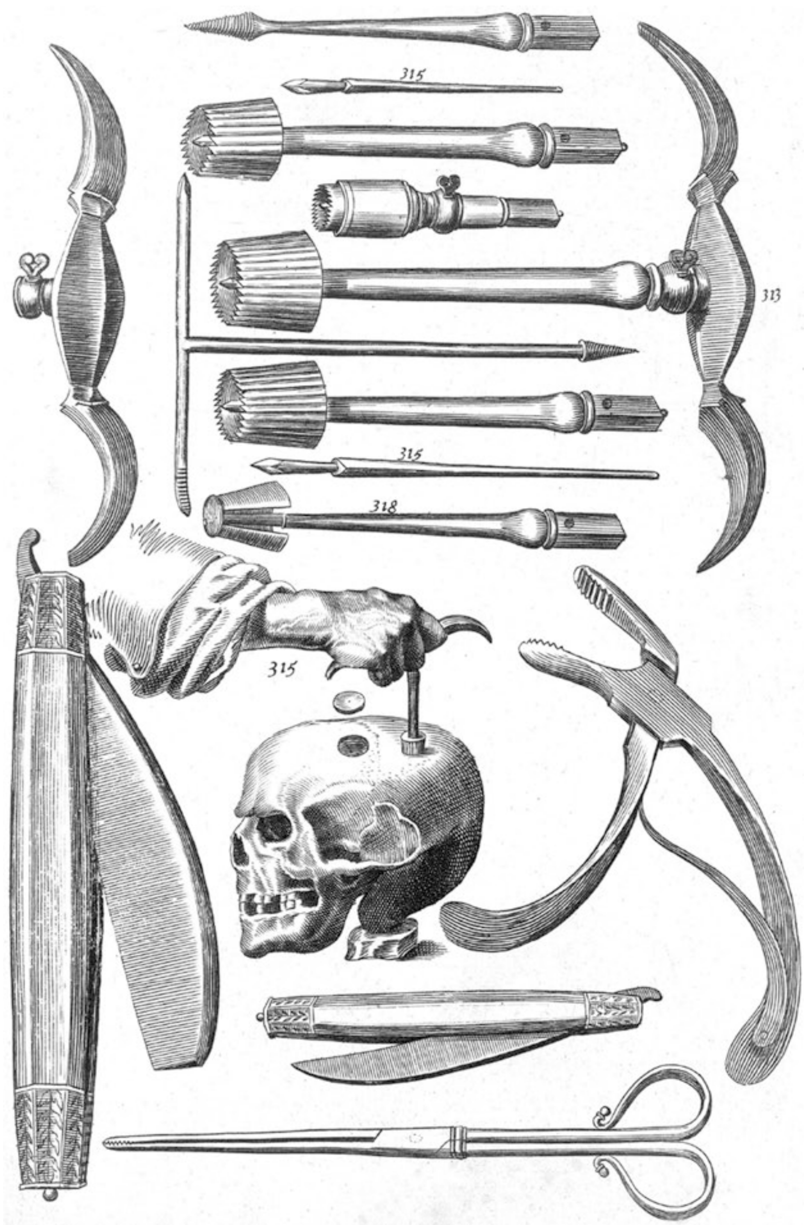

Fig. 11.2 Trepan instruments by John Woodall. In the second edition of the book *'The surgions mate'*, John Woodall includes this new picture of an improved trepan, with a T-handle in 'crane wings' profile (313). The figure includes also some delicate perforators, some crowns with central pin and pins, and a truncated lenticular knife to smooth the internal rim of the hole (318). There are also two spring knives, long forceps to remove foreign bodies and a strong bone forceps for large skull fragments. The figure shows how to work the trepan in a dry skull (Woodall J. The Surgions Mate. London: Edward Griffin; 1639)

mounted on a T-handle forming the trephine or hand-held trephine' [1, 3].

Percivall Pott (1713–1788) postulated the use of the trephine with T-handle as the instrument of choice for cranial trepanations (*'trephining'*) in 1760 [4]. He admitted that it had many advantages and he did not describe any other instrument for trepanation in his book. It seems that this trend shifts from the brace handle to the T-handle took place in London some years before thanks to William Cheselden (1688–1752), a barber surgeon and his apprentice Samuel Sharp (1709–1778). They substituted the brace handle and also recommended cylindrical cutting crowns instead of the truncated conical ones. Pott argued that one of the achievements of 'modern surgery' would be to reduce the number of instruments and their simplicity in comparison with the old ones. Hence, he reduced the number of instruments required for a trepanation, leaving just a trephine with T-handle, a lifter and some forceps (as he admitted that they sometimes were useful). The second advantage was that the trephine with a T-handle allowed carrying out trepanations safely with enough diameter to include the depressed fracture or expose the dura mater in order to drain the supposedly existing epidural collections. He recommended that the handle should neither be too heavy nor too light so that it could be used with just one hand. For this reason, he discarded metal handles. This trend soon spread to English-speaking environments and their areas of influence, particularly North American colonies. These handles with transverse handgrips were so characteristic of British surgeons that French authors from the eighteenth century started calling them *'trépan anglais'*.

11.2.2 Brace-Like Handles

The second successful design onto which the drilling elements could be mounted was the double-bend or brace handle (from the French word *'vilebrequin'*, and this one from the Dutch word *'Wimmelkijn'*; in Spanish *'berbiquí'*). To operate these brace-like handles the surgeon must use both hands. The brace is an old tool that was used in carpentry to make holes on the wood with a drill. Both hands must be used to work with the brace. One must secure the most proximal end of the handle, which exerts an axial pressure on the skull along the axis of the instrument. The other hand is placed on the vertical part of the tool and makes circular movements so that the drilling or cutting element placed on the end spins. The instrument makes a relative rotatory movement with respect to the hand in both hands. This movement can be eased if the instrument has protective covers in the gripping areas to allow the already mentioned rotation. The drilling elements (any of the above mentioned) are mounted on the distal end of the instrument. Depending on the moment of a force, it can be difficult to start drilling with a big drill or a trephine mounted on the brace. For this reason, authors always recommended to start drilling with a fine tip and then place drillers with increasingly large diameters. This fine tip served as a starter and could be mounted either on a borehole or on the brace itself. It could even be the central pin of the trephine.

The brace is a craft instrument. It was probably already known in Ancient Egypt and used by carpenters and masons in Europe during the Middle Ages. However, the first reference about its use applied to trepanation was made by Jacopo Berengario (1457–1530) in his book *'Tractatus de Fractura Calvae sive Cranei'* [5–7].

Berengario described and illustrated the *'vertibulum'*, which had two parts: the handle and the interchangeable drillers (some were used to start the hole and others to enlarge it). He described the *'terebrum canulatum'*, a driller with wings to protect the dura mater avoiding to abruptly invade the intracranial space. However, his true innovation was the brace-like bended handle, although he did not specify where he got the idea from. For this reason, it has been speculated that he might have imported it from carpentry. Maybe he was just the first one who illustrated the brace in a medical work, although other physicians from his school (where he would have learnt how to use it) had used it before.

The use of the brace spread rapidly among the surgeons. Many medical texts make references to it and illustrate it along with the T or borehole handles. An interesting improvement of the design was later developed by René-Croissant Garengot (1688–1759), a surgeon from the regiment of the King of France. Garengot published his book *'Traité des opérations de chirurgie … avec les bandages qui conviennent à chaque appareil'* in 1720 [8]. He described the so-called chin support in the work. He modified the most proximal part of the proximal vertical shank of the brace by coupling a small spinning disc on it that had a concave upper surface. This allowed to lean the chin on it to help the hand in order to maintain a vertical direction and the axial pressure of the brace. This also allowed the surgeon to always see the surgical field in front of him. Although the so-called chin support is usually attributed to Garengot, he described it as the *'methode qui est de Monsieur Petit, comme je l'ai rapporté'* ('method which is of Mr. Petit, as I reported'). Jean-Louis Petit (1674–1750) was an eminent French surgeon who will be reviewed later. From that moment on two styles were established: those who used the chin or forehead support, following Garengot's ideas, and those who preferred to lean the disc of the end of the brace on the chest, particularly on the xiphoid process.

Brace-like drillers that were used with both hands became popular in mainland Europe, such as in France or Central Europe. They coexisted with the borehole but finally substituted it. On the contrary, the borehole was used more frequently in England and Scotland. It was almost the British surgeons' favourite trepanning instrument and ended up spreading to the United States. However, it was finally the Hudson brace handle, which was invented by Robert J. Hudson in 1877, the instrument that continued providing a service in modern neurosurgery. It was used by neurosurgeons worldwide until the end of the last century, when it was substituted by electric or pneumatic motors.

11.3 'Tripolides' Support

A particularly interesting line concerning the design of cranial drilling instruments was some tools in which the drilling element was mounted on a tripod bracket that leaned on the patient's head or torcula-like instruments. It was initially known as 'torcula' or *'terebra extractor'*, as it was initially designed to lift depressed fractures. The word 'torcular' in Latin means wine or oil press. The dictionary of the Real Academia de la Lengua Española (Royal Academy for Spanish Language) includes the term *'tórculo'* (rolling press), which means *'m. Prensa, y en especial la que se usa para estampar grabados en cobre, en acero, etc.'* (masculine noun. Press, particularly the one used to stamp engravings on copper, steel, etc.). The Italian word *'torchio'* also has a similar meaning. The English meaning of the word 'torcular' is tourniquet or bandage. We use the terms 'torcular Herophili' or 'torcula' interchangeably in anatomy when referring to the confluence of the superior sagittal sinus and straight sinus, among others, below the occipital bone. However, there are many doubts about why this anatomical structure is called this way.

The first description of this interesting instrument was done by Hans von Gersdorff (1455?–1529) in the book *'Feldbůch der Wundartzney'* [9]. The instrument with two legs is some kind of compass with an axial axis and a screw-shaped tip. The instrument with three legs (*'tripolides'*) was the most successful one. Each leg had a base that leaned on the head. It also had a thread pitch that allowed to increase or reduce the distance between the bases. The central shank is coaxial and it can be taken forward or removed by a thread pitch depending on the direction of rotation. The distal end of the shank has a spiral thread tip, just like a screw. The aim of the initial design of this instrument was not to drill the skull but to introduce the screw inside a bone fragment to lift it afterwards by reversing the direction of rotation and eventually remove it. In spite of the evident failure concerning the idea and the design of the instrument when aiming to remove fragments of the fracture, this instrument has been described and included in numerous medical texts. It can be found in catalogues of surgical instruments from the beginning of the last century. The design of the torcula has not substantially changed over almost 400 years. However, the accessories of the shank and its use for cranial surgery have experienced some modifications. Hence, the *'tripolides'* has been used as a support for shanks with different working instruments on its end: a screw to lift fragments in a similar way to a corkscrew, a hook or claw to place it under the fragment of fractured bone and lift it, a hook or claw with a coaxial stop that holds the bone fragment like some pincers when screwing it (all these would be lifting torculas) and finally a shank with a trepan or trephine-like driller of small size on its end (drilling torcula).

Many authors criticised the use of this instrument for any of its possible uses as it was dangerous. In spite of that, they described and illustrated it in their books. Considering the design, it is evident how difficult it was to maintain the instrument in a stable position until it grabbed the bone and particularly when it came of piercing it. The risk of dipping the bone fragments inside the skull when lifting them or sliding the lifting portion along the fracture lines seems very high. The hooks or claws should be placed before applying the torcula so that they can be lifted afterwards. This does not involve any advantage when compared to other simpler lifters used in that time.

Some authors expressly described its usefulness for completing the drilling with the trephine. In order to do so, the end of the spiral thread of the vertical shank had to be inserted in the central hole of the bone disc made with the central pin of the trephine itself. Once the screw had been threaded in the bone disc, the direction of rotation was reversed. This allowed to lift the disc of skull by breaking the last connected portions of bone of the internal table. The final purpose of this procedure was to lift the bone disc without using lenticular knives or lifters that could eventually injure the dura mater, as they had to be inserted between the bone and the dura mater.

Finally, the use of the torcula is expressly described for lifting depressed fractures in infants (ping-pong fractures). In this case, a small incision was made on the skin and the end of the shank was screwed to the bone to lift the bone by rotating it in the opposite direction.

11.4 Other Handles

Other very antique handles can be found described in the most ancient books. The acceleration systems for the straight handles that we have explained in the previous chapter were described and illustrated in the medical texts from the fifteenth and sixteenth centuries. They particularly include a simple leather string around the handle of the driller, a string around the handle of the driller and mounted on an arch and finally, a cross-shaped system with a drilled shank in the centre across which the handle of the driller is placed and strings going from the edges of the shank to the edges of the handle. Hence, Vidus Vidius (Guido Guidi, Vido Vidio) (1509–1569) who published his work *'Chirurgia è graeco in latinum conuersa, Vido Vidio Florentino interprete cum nonnullis ejusdem Vidii cõmentarijs'* in 1544, Giovanni Andrea della Croce (c1515–1575) who published *'Chirugiae Universalis Opus* Absolutum' in 1573 and Andrés Alcázar (1500–1584) who published in turn his book *'Chirurgiae libri sex: in quibus multa antiquorum et recentiorum sub obscura loca hactenus non declarata interpretantur'* in 1575 illustrated in an almost identical way these acceleration mechanisms with strings [10–12].

These acceleration mechanisms soon disappeared from the medical texts. This particularly happened after the brace handle became popular, although the authors sometimes referred to them as old instruments. It is probable that the instruments with acceleration systems were abandoned in the middle of the sixteenth century because both Alcázar and della Croce published their books at a very old age, at the end of their long lives. It is possible that straight handles and acceleration systems, which perhaps had been used some decades before by Alcázar and della Croce during their youth, were already obsolete by the time they started writing and publishing their surgical experience with these already obsolete instruments.

There was a late attempt of improvement concerning trepanations by modifying the brace with an interesting assembly of a gear unit. It transmitted the movement of a side crank to the distal shank of the instrument that had a driller. It consisted of a worm drive mechanism and crown that were mounted perpendicular to each other. This instrument, which was not successful, might have had a very poor mechanical efficiency because although the mechanism transmitted great forces a great amount of the power generated was consumed due to the friction.

The crank handle is far more modern. It has a gear unit that turns the manual movement of the crank made by the surgeon into a rotation movement on the axis thanks to a perpendicular gear. The driller is mounted on the end of such gear. J. J. Perret described a similar crank handle in the year 1772. These handles have been successful at a later time and have been used as drillers for fine needles or bits because they seize up easily when they are used with perforators of a larger diameter. More complex transmission systems started being developed at the end of the nineteenth century and the beginning of the twentieth century. They were driven not only by manual cranks or pedals (with the help of the assistants) but also by electric motors. These systems will be explained below.

11.5 Other Cranial Opening Tools

The humble flat or grooved chisel has been used since ancient times to cut the skull bone. It was operated by axially tapping the handle with a hammer that had a heavy head, normally made of wood and filled with lead. This system is efficient and comfortable for the surgeon but it is terrible for the patient, whose head requires to be firmly held. The design of these instruments, excepting for the manufacturing material, has not changed over the centuries. Curiously, it was used as a bone-cutting instrument in the first osteoplastic craniotomy with pedicle flap at the end of the nineteenth century.

Ambroise Paré (1510–1590) described an unprecedented cranial drilling system similar to a compass [13]. It had one sharpened point that served as a central support and another sharpened point that cut a disc of bone by repetitive rotation. He used a metal template with holes which bent so that it could be adapted to the head in order to lean the compass safely. The diameter of the drilling disc could be adjusted by means of a screw placed between both axes of the compass. Giuseppe Zuccaro recovered this design in 1894 with an instrument that had a central axis with a pin that was secured to the skull. It also had a distal horizontal bar onto which a needle was fixed to cut the bone. The rotation movements on the central axis cause the coaxial needle to go deeper inside the skull and carve a perfect circle. It is possible to obtain cranial openings with a different size and shape by applying different cutting centres.

F. Terrier and M. Péraire described a great number of trepanation systems in their book '*L'operation du trépan*', which was published at the end of the nineteenth century [14]. These systems had been used by the authors in surgical procedures or had been tested on corpses by them. One of them was Tauber's '*tomotrephine*'. It was a clever system that allowed to obtain perfect bone discs with bevelled edges. According to the author, this made it easier to place them back after the surgery when applicable. He also described a series of drillers that he generically called by 'external support'. Poulet's trepan had an external crown that firmly leaned on the skull with a handle. It also had a second internal crown that had a separate handle and was used for cutting. They also described a similar instrument that allowed making semicircular perforations invented by Farabeuf. This trepan allowed removing small crescent pieces of skull in order to enlarge the perforations. The main characteristic of this instrument was that it leaned on some forceps that clamped on the edge of the cranial hole. In contrast, the so-called Poirier craniotome or 'forceps-saw' was an instrument to cut manually the skull with a circular saw just like modern electric tin openers. The instrument had some forceps with a dura mater protection that was fixed to the bone and an integrated circular saw that cut over the protection. However, the saw had a poor cutting power and therefore the cuts had to be made following previously marked lines which were made on the skull with a Hey's handsaw.

11.6 Instruments for Lifting Bone Fragments

As the trepanation has been related to the treatment of cranial fractures for many centuries, many instruments aimed at lifting the depressed bone fragments have been used to help during the procedure. The so-called lifters are instruments that have been described since ancient times. They have had different names, sizes and shapes. However, they basically consisted of solid, long, metal pieces. They were often curved and had a flat and blunt edge and a handle. One or both ends could be usable. They were used by placing the flat end between the dura mater and the bone fragment to be lifted. They used the intact edge of the skull as a supporting point in order to lever and lift the free bone fragment.

Other more complex lifters were based on those easel-like levers with a supporting point on the surface of the skull and a tilting shank with a final or sliding hook. This hook lifted the fragment like a crane after hooking it from below or grabbing it with some forceps. The first system of this kind was described by the German author Wilhelm Fabry von Hilden (1560–1634) in 1641 and illustrated later by others [15]. However, it was improved in many versions afterwards. Hans von Gersdorff (1455?–1529) described for the first time a lifting system for fractures with a hook mounted on a torcula [9].

Bone fragments can also be caught and lifted with simple forceps that are strong enough. However, if they are embedded a more powerful and stable grabbing system is required. Some grabbing instruments similar to a pair of pincers were developed for this purpose. Some of them had a thread pitch to coaxially bring the gripping tips closer and secure it. This instrument was already illustrated in the text written by Jacques Guillemeau (1550–1584) *'La chirurgie françoise, recueillie des Anciens Medecins et Chirurgiens avec plusieurs figures des Instrumens necesseres pour l'operation manuelle'*, which was published in 1594 [16]. It also appeared later in other texts with a few modifications concerning its design until it finally disappeared.

11.7 Instruments for Enlarging the Initial Cranial Perforation

Trepanations have been made to treat fractures for centuries. Eventually, they were carried out to explore the epidural space and drain the blood or purulent accumulations. The cranial opening provided by the trephine was large enough over centuries to meet these needs. Physicians sometimes raised the need for enlarging the cranial window made with the trepan or trephine drillers or caused by the cranial injury itself. In order to do so a series of instruments aimed exclusively at enlarging the cranial opening have been used, particularly when operating depressed comminuted fractures.

Bone forceps aimed at breaking the bone of the cranial vault have been used to enlarge cranial openings since ancient times. There are two systems, shear-like cutting forceps and gouge-like punches. Any type of bone forceps is efficient but they are heavy for the surgeon and traumatic for the patient as they require a lot of force and they need the head to be firmly fixed. These forceps have been used until very recent times.

The simple saw has been used to cut the skull bone since ancient times. Cranial saws are generally short, flat and thin and have short teeth. They are mounted on a handle and have one straight side and an opposite one which is more or less rounded and convex. Ancient authors recommended opening the skull with the saw. However, these saws were not adequately illustrated in the medical texts until the sixteenth century. Giovanni Andrea della Croce (c1515–1575) published *'Chirugiae Universalis Opus Absolutum'* in 1573 [11]. The book included drawings of six different types of cranial saws. In contrast to general bone saws, cranial saws were shorter and had less teeth. Some authors supported the idea of using the saw as an alternative option to drillers. Its exclusive use as a cranial opening system started going down during the seventeenth century. However, they were always used as a help to enlarge the cranial opening or to complete the lifting or removal of the fragments in case of complex fractures. The most successful cranial saw in the nineteenth century was the one designed by William Hey (1736–1819).

Mechanical saws were soon invented, probably due to the troubles when cutting the flat bone of the skull or the patient's suffering during the procedure. However, these saws were not very successful due to their poor mechanical efficiency. These saws, which could make circular or swinging cuts, required gears that were manually operated by cranks. One of the first mechanical saws was described by Johannes Scultetus (1595–1645) in his *'Armamentarium chirurgicum'*, which was published in 1655 [17, 18]. It was a saw that made cuts by swinging movements. It was manually driven and had a gear system. Bernhard Heine (1800–1846), a German physician and orthopaedic surgeon from the nineteenth century, invented and presented the *'osteotome'* in 1830. It was the first design in the world that involved a chain saw that was manually driven with a crank. It had a relative and ephemeral success in Central Europe for medical use. Its design was granted an award by the Academy of Sciences of Paris in 1835. However, it was later successfully introduced in the industrial field. The use of the saw was very unstable for the skull. It involved a high risk of dural injury as it cut from outside-inward. In addition, it was expensive and difficult to use and had frequent failures. A large pin was added to the saw to fix it to the skull during its use and solve the first problem. However, the reason why it became obsolete was due to other problems. Finally, all manual or electric chain saws stopped being used when Leonardo Gigli (1863–1908) introduced the twisted saw named after him at the end of the nineteenth century.

The lenticular knife is an instrument that had been well described since the sixteenth century, for example by Ambroise Paré (1510–1590) in his *'Methode curative des playes et fractures de la teste humaine'*, which was published in 1561 [13]. The instrument is a symbiotic evolution of two of the most ancient instruments, particularly the chisel and the *'meningophylax'*. It was a side-cutting chisel with a distal lenticular plate or enlargement to protect the dura mater. It was used to cut the bone by tapping perpendicular to its axis with a lead hammer. It could also be used for less aggressive actions to homogenise the edges of the cranial opening by using it manually just like when peeling a fruit with a knife. The lenticular plate is placed between the bone and the dura mater so that the latter can be protected from the cut. The lenticular knife was modified in the seventeenth century. It had an incomplete truncated cone shape and the size of the trephine crowns in order to harmonise the unevennesses of the hole and pick up the rests of the bone from the inside. This instrument finally became obsolete at the beginning of the nineteenth century.

11.8 Other Instruments Used in Cranial Surgery

Apart from the general instruments that were necessary and accepted for any surgery in any period of time, such as forceps, scissors, suture needles, instruments for cauterisation or probes and catheters for exploration, there are some instruments with a particular use in cranial surgery that we are going to describe briefly.

The *'tirefond'* are metal shanks with a helical shaped end similar to a screw or a corkscrew. They were aimed at skewering bone fragments to remove them, particularly cranial discs obtained after drilling with a trephine. In the case of drills made with the central pin of the trephines, the *'tirefond'* was screwed in the hole made by the pin. The instrument was mounted on a straight or T-handle, which was interchangeable with other handles in many cases. When the *'tirefond'* was inserted, there was a risk of sinking the fragment in the skull if it was free. For this reason, the surgeon had to be very careful. This was the application of the *'tirefond'* mounted on the torcula-like instrument that was previously described. An alternative option to the insertion of the *'tirefond'* was lifting the bone fragment with a bent dissector or lifter. For this reason, Y-shaped instruments (*'tirefons à trois pieds'*) started being designed from the sixteenth century. They had a different system (normally a *'tirefond'* and two lifters) mounted on each of the three arms. The *'tirefond'* was also used to lift depressed fractures in infants, called nowadays ping-pong fractures. Surgeons tried first to lift these fractures with different types of suction manoeuvres or glues, but in case of failure the instrument was screwed to the bone through a small skin incision. They were lifted by pulling from the handle or with a three-legged torcula.

The scrappers (*'rugines'*) are instruments that already existed in ancient times. Their purpose is to remove the soft tissues from the bone, either the periosteum or the rest of the pericranial soft tissues, particularly the galea aponeurotica. Scrappers have been called differently over the centuries. They were called *'cycliscis'* in the oldest texts and later *'scalpra'* and finally it was substituted by the French name *'rugine'* for centuries. Cleaning the bone was essential to identify the fractures and the cranial sutures and apply the drillers safely. It was also argued that trepanning on soft tissues was very painful for the patient.

The shapes and designs of the scrappers have been very different. In addition, they were similar instruments or had a similar use than lifters or dissectors. These instruments are still used nowadays and we generically call them in English periosteal elevators. Some authors recommend the use of scrappers to remove the outer table of the skull and explore the diploe and the internal table, even by making a small cranial opening without using the saw or drillers. They were also used to remove the fracture lines until making them disappear.

The *'meningophylax'* was a classical instrument from Hippocratic times aimed at protecting the dura mater. It was shown as a simple plate connected to an angled handle in the first descriptions. It just aimed to separate the dura mater from the bone and protect the former while cutting the bone. The design changed over time and the instrument became sharper, resembling a current dissector. Its use also changed and it focused on dissecting rather than on protecting. The distal end was enhanced later. It became enlarged and had the shape of a lentil. For this reason, they started calling it lenticular or 'lenticular depressor'. It aimed to separate the dura mater from the sutures or even the venous sinuses again. Finally, the lenticular was merged with the chisel and became a new instrument, the lenticular knife. It basically cut the bone with one of its sides and had the lenticular plate to protect the dura mater placed on one end.

Bone sawdust is produced during the trepanation, either with a drill or a trephine. It spreads all over the cutting elements. There were already references about the importance of cleaning the bone sawdust in the Hippocratic texts. For this reason, there was always a flat ebony wood or ivory brush with horsehair among the trepanation instruments to clean the bone sawdust produced by the trepanation of either the surgical field or particularly the cutting crown of the drillers. These brushes were completely manufactured (both the handle and the hair) in metal after the sterilisation techniques were introduced. They were later removed from the cases of surgical instruments due to the troubles for cleaning and sterilising them.

11.9 Cases and Sets for Trepanation

Many medical treatises of this period of time show the surgical instruments in prints or sheets that are separate from the text. The instruments required for trepanations were soon gathered and represented in one or two prints. They were put together to make the most of the available space on the page. After checking real instruments, researchers have been able to demonstrate that they were kept in cases for this purpose. The organisation of the instruments in the illustrations of the books corresponds exactly with the instrument cases.

Cases with sets of trepanation instruments were made in the seventeenth century. However, there was no concern about aseptic techniques in that time. The instruments were manufactured in metal and other materials such as wood, ivory or bone. They were only cleaned to keep the instruments tidy and well maintained. The cases were made of wood and normally had cushions and gaps, lined with rich fabrics like silk or velvet, to embed each instrument. These instrument sets were kept until the antiseptic techniques started. It seems that they come from European English-speaking territories and they were particularly useful in naval and war surgery, as they contained the instruments recommended by the corresponding health services. Actually, the first surgical instrument cases or chests were for naval surgeons. They had to make sure that they had all necessary material to carry out the most frequent interventions during the whole journey. Trepanation and amputation cases were made for this purpose. They frequently contained the instruments required for both types of surgery. There are many beautiful cases and kits of this kind in museums and antique shops that date back to the seventeenth–nineteenth centuries. The collection of surgical instrument kits, particularly those for trepanation, is pretty rich in Europe during the eighteenth century. It included brace-like handles and crown drillers. It was also pretty wide in the United States during the second half of the nineteenth century, with T-handles and trephine-like drillers. The latest kits included instruments made in stainless steel to allow their sterilisation by boiling them. They disappeared at the end of the nineteenth century as there was no point in keeping the material in wood cases.

War surgery meant the training programme of many great surgeons of that time. The instrument cases and sets were particularly useful for this purpose. The surgeons of the armies carried their own instrument cases, which they had normally bought themselves. In the navy, the surgeons had to take with them all necessary material for surgical procedures during the whole journey. Hence, they had to take inventory and some surgeons published lists with the required instruments. An interesting example was John Woodall (1570–1643), an English military surgeon who was the author of the book *'The Surgions Mate'*, in which he reviewed the instruments and stock of drugs that surgeons and barbers enlisted in the Royal East India Company (where he was appointed Surgeon General) had to take with them in their chests [1]. The Vereenigde Oost-Indische Compagnie of the Netherlands followed the same model and so did the Spanish Armada Real Española.

These kits, particularly those for trepanation, were developed in a military field but they were later taken to civil practice in the last decades of the nineteenth century. They even became a gift for new physicians in their graduation party from their relatives or friends or for faculties or lecturers from recently graduated physicians. The compact instrument cases were also useful for surgeons who carried out interventions aside from those in the hospital. They purchased them according to their needs.

Catalogues of surgical instruments include cases and sets suited for general surgery or designed for particular purposes. Arnold and Sons were manufacturers of surgical instruments from London. In their illustrated catalogue of surgical instruments published in London in the year 1873, several pages collect the surgical instruments recommended by the Navy and the Army for the different types of vessels and companies [19]. A superior mahogany case, brass-bound and lined with silk velvet, contained the instruments. The composition of instruments of each set, in accordance with the Army Regulations, is detailed. Cases included in the catalogue were Army Regulation Case; Set of instruments for a surgeon in the Royal Navy; Set of instruments for an assistant surgeon in the Royal Navy; Set of instruments required by a surgeon appointed to the Royal Navy Steam-packed Company; Set of instruments required by a surgeon appointed to the Peninsular and Oriental Navigation Company; and Set of instruments required by a surgeon appointed to an emigrant ship. All of these cases had instruments for cranial surgery, including trephines, Hey's skull saw, skull elevators and forceps, trephine brush and spring probing. Evans & Wormull manufactures also from London have in their illustrated catalogue of 1876 cases of instruments for surgeons of the Army containing instruments for trephining (Army surgeons' regulation case; Army hospital case) [20].

The need for sterilising the instruments with the aseptic techniques forced surgeons to operate in hospitals, where the instruments (which were completely made in stainless steel) could be sterilised and stored. Old cases became obsoletes and collector's items or museum pieces over time, and instruments were purchased by hospitals' administrations. Meanwhile, surgeons purchased diagnosis tools and minor surgery instruments for their private practices and offices.

Instruments for trepanation, amputation and osteotomy were illustrated together in catalogues. The catalogue by George Tiemann & Co. shows a large number of bone drills and drills mounted on straight, T- or brace handles; cylindrical, guarded and truncated cone of Galt trephines with brace and T-handles; forceps; Hey's saw; different types of circular saws; Heine's saw or osteotome; and a large number of bone forceps, elevators, osteotomes and hammers [21].

11.10 Comments

We have made a quick review of the instruments used for trepanation throughout the Modern Age, a long period of time where there were few technological innovations. There was a change in the use of some instruments, others were abandoned and there were some new designs. However, all the instruments were variations of the medieval models based in turn on the Greco-Roman designs.

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12 'State of the Art' of the Trepanation During the Sixteenth and Seventeenth Centuries

The trepanation might have been carried out in very sporadic times during this period of time. However, the large number of texts of medicine and surgery that address cranial injuries and trepanation and describe the necessary instruments suggest that the technique was well known by the surgeons of the time, and was the reason why the use of this procedure increased during this time.

We can affirm that medical books of that time strictly followed what was included and suggested in the Hippocratic texts. Trepanation was only indicated for cranial trauma and wounds on the head, either in acute stages or when there were complications. Some authors recommended trepanning in the case of evident or suspected fractures but this clashed with the lack of secure diagnostic methods apart from the direct examination of the wound (when applicable). Even so, it was difficult to confirm that there was a fracture in many cases, particularly in those ones with linear fractures. In the case of cranial contusion without a wound the fracture was suspected just by palpating the skull and identifying an area with selective pain. If there was a wound, the surface of the skull was visually examined or palpated with the fingers. The margins of the wound were separated or the wound was enlarged with release incisions that were preferably cross-shaped. Two methods were used to accurately identify the fracture line or distinguish it from cranial sutures. One of them, which was already described in the Hippocratic texts, consisted of applying ink over the surface of the skull. The physician checked how it accumulated in the real fracture line some hours after. The other method consisted of asking the patient to firmly close the mouth or both the mouth and the nose. Then he was asked to take deep breaths, in a similar way to the Valsalva manoeuvre, so that the physicians could check whether there was blood coming out from the real fracture line.

Concerning the trepanation instruments, each author described and illustrated his or her own instruments. They were nothing but the evolution of those instruments described in the Greco-Roman period. There were not significant revolutions concerning the design or the use. All instruments looked similar, although the illustrations were more detailed and had more quality as time went by.

Trepanations were carried out by surgeons who were authorised for these procedures after a training period with a renowned surgeon or rarely with surgeons who had been trained in the schools of medicine where surgery was taught. One of the limitations concerning the training of surgeons was the scarce knowledge they had about Latin, as medical texts of that time were written in that language. This fostered the publication of surgery texts in vernacular languages. Surgeons had to learn the surgical techniques that were clearly described in the texts, as well as having a good command of anatomy, physiology and general medical treatments. For this reason, they

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considered themselves superior to physicians or physicists, who despised them in turn.

Schools of medicine started offering a degree in medicine that authorised to practise medicine and surgery. The medical assistance offered to the population had been stratified in groups since classical Greece. Medical support was classified in several levels: the assistance given to kings, noblemen and magnates by the chamber physicians, who were normally eminent figures; the assistance given to bourgeoisie at their own homes under minimal hygiene conditions concerning current parameters by prestigious private physicians; and finally the assistance given to workers, artisans and poor people at their homes, in the streets or in foul hospitals that lacked any hygiene or sanitary control. A similar level of assistance, which was even more deplorable, was offered to injured soldiers in the battles. Paradoxically, the evident inefficiency of the treatments equalled the clinical results, regardless of the healthcare level. However, the role of hospitals visibly improved from the Renaissance on, particularly their architectural design. There were also changes on their mission, as they went from a charitable purpose, then a philanthropic one, to a later clinical purpose until they finally started gathering scientific studies and technical advances, in other words modernity.

There were three categories of professionals that practised medicine in England during the Tudor period, which corresponds with the sixteenth century [1]. Physicians, who got their degrees at university, and the highly qualified members of the Fellowship of Surgeons, who were also trained at university and could practise both medicine and surgery, were at the highest level. Barber surgeons of the Barbers Company were placed at the next level. They were trained by a surgeon master over 7–9 years and then had to pass a qualifying exam. Lastly, there were barbers who could work as assistants for surgeons or barber surgeons, as well as pharmacists, quacks, herbalists and astrologers. King Henry VIII granted the barber surgeons a charter in 1540.

The situation was even more difficult in Scotland as the resources were more limited. Surgery was taught in Glasgow after a training period with a master of at least 5 years. Afterwards they had to take an exam. Physicians, on the contrary, required a certification issued by a school of medicine. As there was no such school in Glasgow, students had to be trained in London or in mainland Europe. Peter Lowe and Robert Hamilton were granted a royal charter by James IV of Scotland in 1599. They founded the Faculty of Physicians and Surgeons in Glasgow which was in charge of organising the medical, surgical and pharmaceutical professions and pursuing unqualified workers, particularly barbers, in a wide geographic area that covered the South-West of Scotland. Barbers only achieved autonomy at the end of the eighteenth century.

The same system of traditional training for barber surgeons was followed in the Netherlands in the sixteenth century. They started as pupils or apprentices (*'leerknecht'*) at about 10 or 15 years of age, depending on the town. They eventually became masters (*'meester'*) but there was an intermediate level called *'knechten'* within the association of barber surgeons. To become a master, they had to be registered in each level of the association for 2 or 3 years. The training possibilities depended on the town. There were lessons taught at the *'Theatrum Anatomicum'* of many towns which included anatomical dissections of corpses of people who had been executed. Some of these practices were illustrated in beautiful paintings, such as *'The Anatomy Lesson of Dr. Nicolaes Tulp',* painted by Rembrandt in 1632. The exam to become a master consisted of a theoretical part and a practical one. The exam included the practice of trepanning a skull in the eighteenth century.

The situation was very similar in German towns. To practise surgery in Cologne at the end of the sixteenth century an authorisation was necessary from the Barber Company. Surgeons who had not been trained in the town could buy their licence. This is what Wilheim Fabry, who will be mentioned later, did on the 25th of June of 1599. However, he did not pay it all and owed a certain amount. The Barber Company had a commission with four members who could revoke the licence and suspend a surgeon if they disagreed with any of their treatments. However, in Germany the organisation of the surgical activity lasted until the seventeenth century. Only in 1734 Prussia published a law compelling barber surgeon to serve 3-year apprenticeship, pass an examination and spend 3 years more assisting and living with their masters. Very famous German surgeons related with the trepanations were actually barber surgeons, trained and learned by themselves. This is the case of Hans von Gersdorff [2].

An important part of the surgical practice was carried out in battlefields and during wars in Europe. It was less often carried out in hospitals and at home. Luckily, we have detailed descriptions of those cases that affected members of the court. They give us some idea about the situations in which trepanations were carried out in particular cases.

A dramatic well-documented case of cranial trauma was the injury of the king Henry II of France (1519–1559) [3]. He was hurt during a jousting tournament that took place coinciding with the wedding of his daughter Elizabeth with Felipe II, king of Spain at the Place des Vosges in Paris on the 30th of June of 1559. The king was injured in an eye with the broken lance of his opponent as it penetrated the visor of his helmet. The king was attended for 10 days until his death on the 10th of July by 'five or six of the most expert surgeons in France who took all necessary actions to go deeper in the wound and examine the closest area to the brain, as there could be splinters from the end of the lance. However, they did not succeed. They would not have achieved it even if they had carried out anatomical dissections on four heads of executed convicts, who were beheaded at the Palais de la Cité or the prisons of the Grand Châtelet. The broken lance went deeper inside their heads with enough force to let them experiment. Nevertheless, it was all in vain'. Ambroise Paré was among the surgeons who attended the king, whereas Felipe II brought Andreas Vesalius from Brussels. However, he could do nothing to save the king's life as he had already died by the time he arrived.

Another well-documented historical event that is related to trepanation was the cranial trauma who suffered prince Carlos, son of the emperor Felipe II of Spain. Prince Carlos was a young man with important behavioural disorders, deformities and diseases [4]. He fell from the stairs in Alcalá de Henares (Spain) on the 19th of April of 1562. He was hit on the occipital region and suffered a cranial blunt trauma on the lambdoid suture region. He underwent a cranial scrape on the 9th of May. He was officially discharged after 93 days of treatment. Dionisio Daza Chacón (1510–1596), one of his physicians, described in detail the injury, the pathology and the treatments in his report *'Relacion verdadera de la herida de la cabeza del Serenísimo príncipe D. Carlos nuestro señor, de gloriosa memoria, la cual se acabó en fin de julio del año de 1563'* (Actual description of the wound on the head of His Serene Highness Prince Carlos, of glorious memory, which ended at the end of July of year 1563), included in the book *'De la practica y teórica de la cirugía en romance y latín'* published in 1595 [5]. It is a great example of a medical record accompanied by accounts about the discussions, meetings, reflections and proposals of the physicians and surgeons involved in the treatment of the prince. They met in dozens of *'consejos'* ('councils') that took many hours, sometimes with the attendance of the powerful emperor Felipe II. After the prince fell down he was subjected to treatments and bloodlettings according to the standard procedures of that time. The wound was examined and a fracture was discarded. The prince's condition worsened as he showed erysipelas, fever and delirium. King Felipe brought eminent physicians and surgeons, including a Portuguese surgeon and Andreas Vesalius himself, to care for Carlos. They had three different points of view. Vesalius supported trepanation as he thought that there was an accumulation under the bone. Others stood for the non-surgical treatment as they stated that the problem was the infection of the wound. Finally, other experts such as Daza Chacón suggested a mere scraping of the outer table of the skull as they thought that the problem was between the two tables of the skull. The situation was so critical that on the 9th of May they decided to carry out a scraping. It was carried out by Daza Chacón under the orders of the Duke of Alba, who attended the intervention along with the rest of physicians and surgeons. The king Felipe II was in the next room. Daza Chacón said: 'The Portuguese physician took the curette. However, shortly after the Duke of Alba ordered me to do it. I started scraping and soon found the white and solid skull. Some small bright red blood drops started coming out from the pores of the bone, so I stopped scraping'. According to these findings they concluded that there was no cranial damage, either between the tables of the bone or intracranial effusions ('We could check with our own eyes that there were no damages to the skull, not even in the internal area that was below that point. This allowed to clear all doubts and this way, all of us, except for Vesalius and the Portuguese physician who never changed their mind, understood that the damage was accidental and caused by the fever and the erysipelas'). Despite the cranial surgery, they made a fatal prognosis for Carlos and Felipe II left as he did not want to see his son die. The mummy of the monk Diego was brought to the room and they applied some ointments made by a Moor from Valencia to the wound. That night, for whatever reason, the prince's condition surprisingly improved. He finally got over after a torment of treatments and dressings.

Prince Carlos died 6 years later in circumstances not clarified. The stormy relations with his father and his stepmother and his political ambitions were picked up in the drama *'Dom Karlos, Infant von Spanien'* by the German writer Friedrich Schiller of 1787, which would serve as the basis for the famous opera *'Don Carlos'* by Giussepi Verdi, premiered in the year 1867. Here the prince is presented without any physical or psychological defect.

The available documentary information seems to prove that the interest on trepanning and the development of the required instruments took place almost exclusively in France, Italy and Spain. There is evidence about the fact that the trepanation and the trepan were unknown or scarcely carried out in Central Europe during the first half of the sixteenth century. Hence, the physician Johannes Lange (1485–1565), who was born in Silesia and studied surgery in Italy, went back to Germany carrying a trepan that was an unknown instrument in the Palatinate. The Spanish surgeon Dionisio Daza Chacón (1510–1596), who served emperors Carlos V and Felipe II, also wrote that head wounds were treated 'without tools' in Germany.

Trepanation was only indicated for head wounds and fractures. However, there is evidence that it was used for other conditions in the seventeenth century, such as syphilitic headaches, epilepsy or melancholy. This is the reason why there are references about people who were trepanned in multiple occasions. Some surgeons also started to raise the need for trepanning fractures or complications derived from fractures, such as blood or purulent accumulations or late epilepsy in the seventeenth century. Another aspect that caused much controversy and led to many modifications of the trepanning technique was the evidence of fractures in the internal table of the skull without fractures of the outer table and the problems caused due to a diploe contusion.

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13 Relevant French, Italian and Spanish Surgeons in Trepanation over the Sixteenth and Seventeenth Centuries

During the sixteenth and seventeenth centuries the centre of the medical and surgical activity and development was in the areas involved in the Renaissance cultural movement. Trepanation was performed and developed particularly in France, Italy and Spain, with marginal contributions by British and German authors. In this chapter, we are going to describe the recommendations and instruments of two relevant French authors (Ambroise Paré and Jacques Guillemeau) to illustrate the practice of trepanation in the sixteenth–seventeenth centuries. We are going to mention as well the Italian authors Giovanni della Croce, Giovanni De Vigo, Fabricio d'Acquapendente, Jacopo Berengario and Leonardo Bottallo and a selected group of Spanish surgeons involved in the cranial surgery and trepanation, such as Andrés Alcázar, Francisco Arceo and Dionisio Daza Chacón.

13.1 French Surgeons: Paré and Guillemeau

Ambroise Paré (1510–1590) was a French surgeon who worked for several kings of France. As he had humble origins and no training he started as a barber surgeon and then became an army surgeon. He published the *'Methode curative des playes et fractures de la teste humaine'* in French in 1561 [1]. This book showed and described accurately the instruments required for trepanning, as well as their use (Fig. 13.1). According to Paré, to carry out a trepanation some instruments are required: a knife, a pericranial scrapper, bone scrappers (*'rugines'*), a T tool with a screw tip (*'tirefons'*), another tool with three legs (*'tirefons a trois branches'*) one of them having a screw tip and the others flat lifting tips, bone saws for the skull, bone lifters similar to strong dissectors and others similar to a pair of pincers with a screw system to grab, a torcula-like skull bone fragment lifter with three legs (*'elevatoire à trois pieds'*), chisels, mallets and forceps. As for the drilling instruments, he preferred the brace-like handle. Concerning the perforating tip, he described an exfoliating drill, consisting of a square lancet with central tip and bevelled edge on both sides, and the trephine crown, which he called *'la trepane'*. He shows all the elements that characterise this instrument: central pin, cylindrical driller with serrated crown and peripheral case or cap that prevented the instrument from dipping inside the skull, with a sliding stop to adjust the cutting depth. He described an instrument with a T-shaped handle and a sharp tip on its distal end similar to a punch (*'Foret por commencer a oubrir le crane'*) to start the perforation. Finally, he illustrated in detail the instrument required for making the bone cut safely, without injuring the dura mater. This instrument, known as *'lenticulaire'*, was nothing but a chisel with a side-cutting edge and a lenticular sheet to protect the dura mater. It was used to cut the bone

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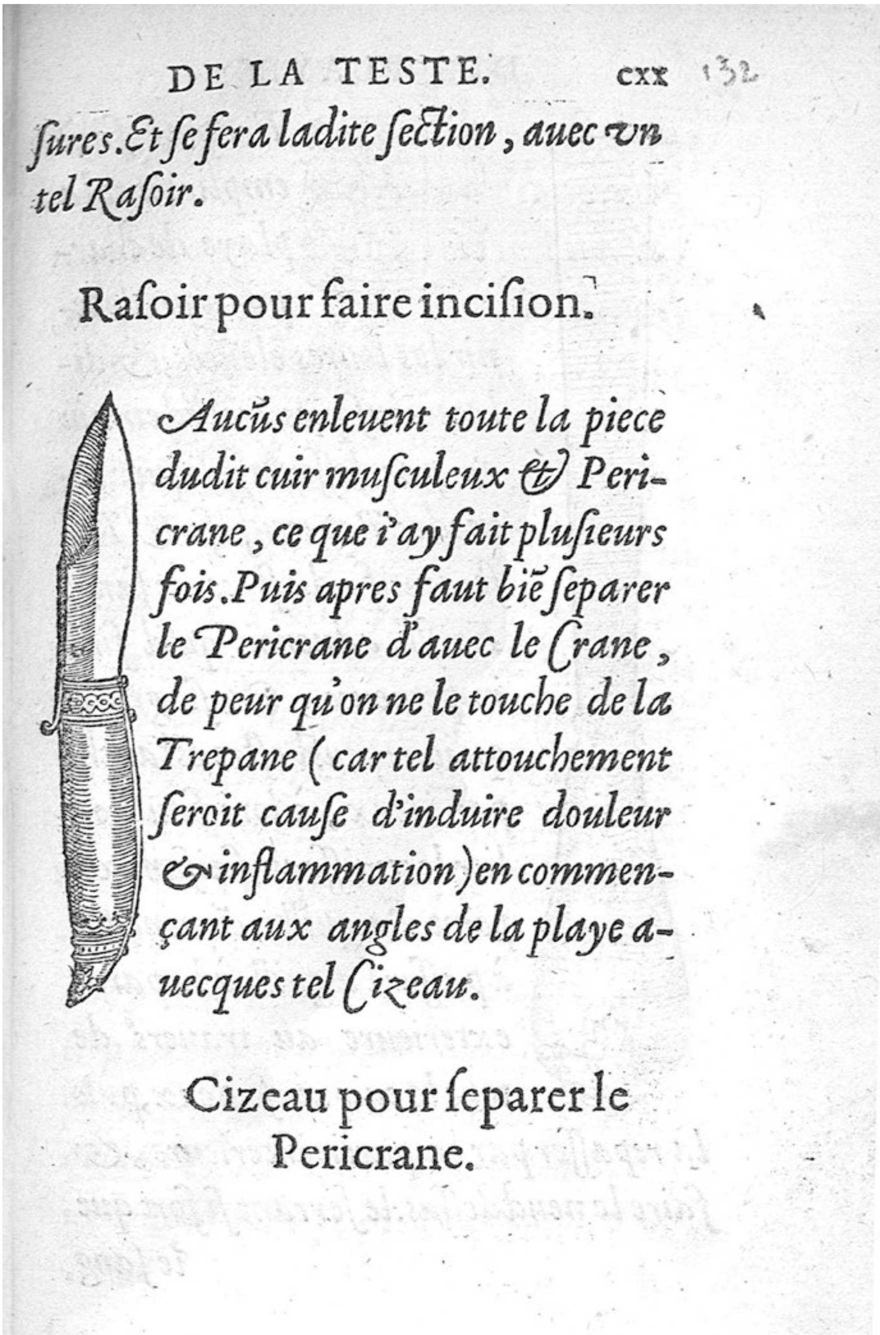

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ſures. Et ſe fera ladite ſection, auec vn tel Raſoir.

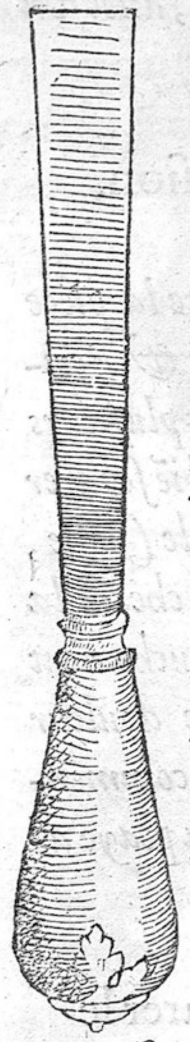
Raſoir pour faire inciſion.

Aucũs enleuent toute la piece dudit cuir muſculeux & Pericrane, ce que i'ay fait pluſieurs fois. Puis apres faut biẽ ſeparer le Pericrane d'auec le Crane, de peur qu'on ne le touche de la Trepane (car tel attouchement ſeroit cauſe d'induire douleur & inflammation) en commençant aux angles de la playe auecques tel Cizeau.

Cizeau pour ſeparer le Pericrane.

Fig. 13.1 Instruments related to the trepanation by Ambroise Paré (Paré A. Methode curative des playes et fractures de la teste humaine. Paris: Chez Jehan Le Royer; 1561)

DES PLAYES



ET apres faut emplir toute la playe de charpy : à fin de tenir les leures eleuees, & dilatees iuſques au l'ẽdemain & par deſſus appliquer remedes Repercuſſifs & Reſtraintifs du flux de ſang. Et ſ'il aduenoit qu'il fuſt impetueux, & ſi grand qu'il ne peuſt eſtre eſtanché par iceux, à lors faudroit lier le vaiſſeau, faiſant vn point d'aiguille, cõmençant à paſſer l'aiguille à la partie exterieure au trauers de tout le cuir muſculeux, puis la repaſſer par la partie interieure, & faire le neud deſſus: le ſerrant ſi fort que

le ſang

Fig. 13.1 (continued)

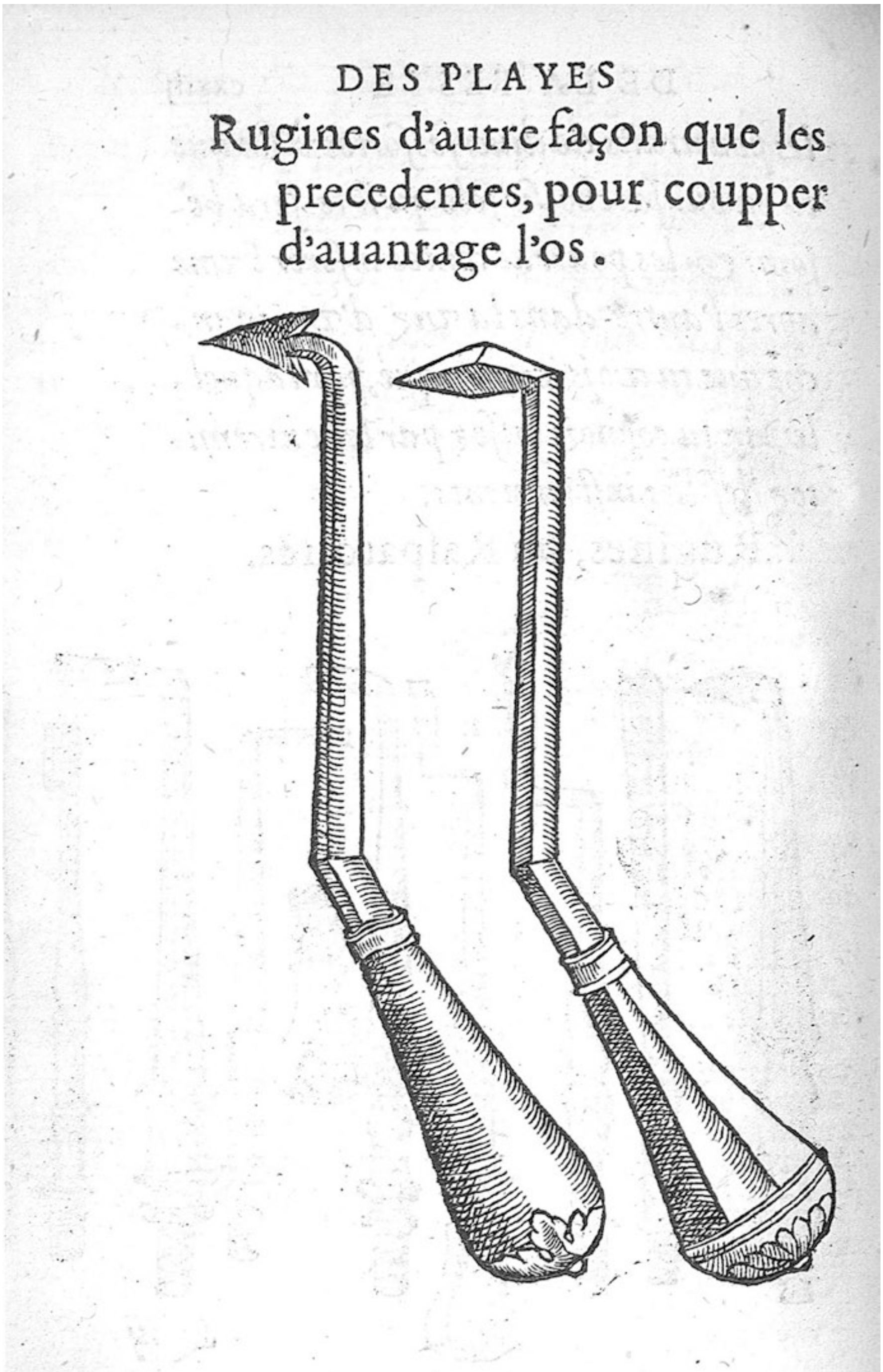
DE LA TESTE cxxiij 135

les pourtraits de diuerſes ſortes: à fin que tu en puiſſes choiſir ſelō qu'il te ſera beſoin: & les pourras toutes inſerer l'vne apres l'autre dans la viz d'vn manche que tu vois icy merqué, par laquelle viz tu cognois aſſez par les extremitez deſdits inſtruments.

Rugines, ou Raſpatoires.

Q iij

Fig. 13.1 (continued)



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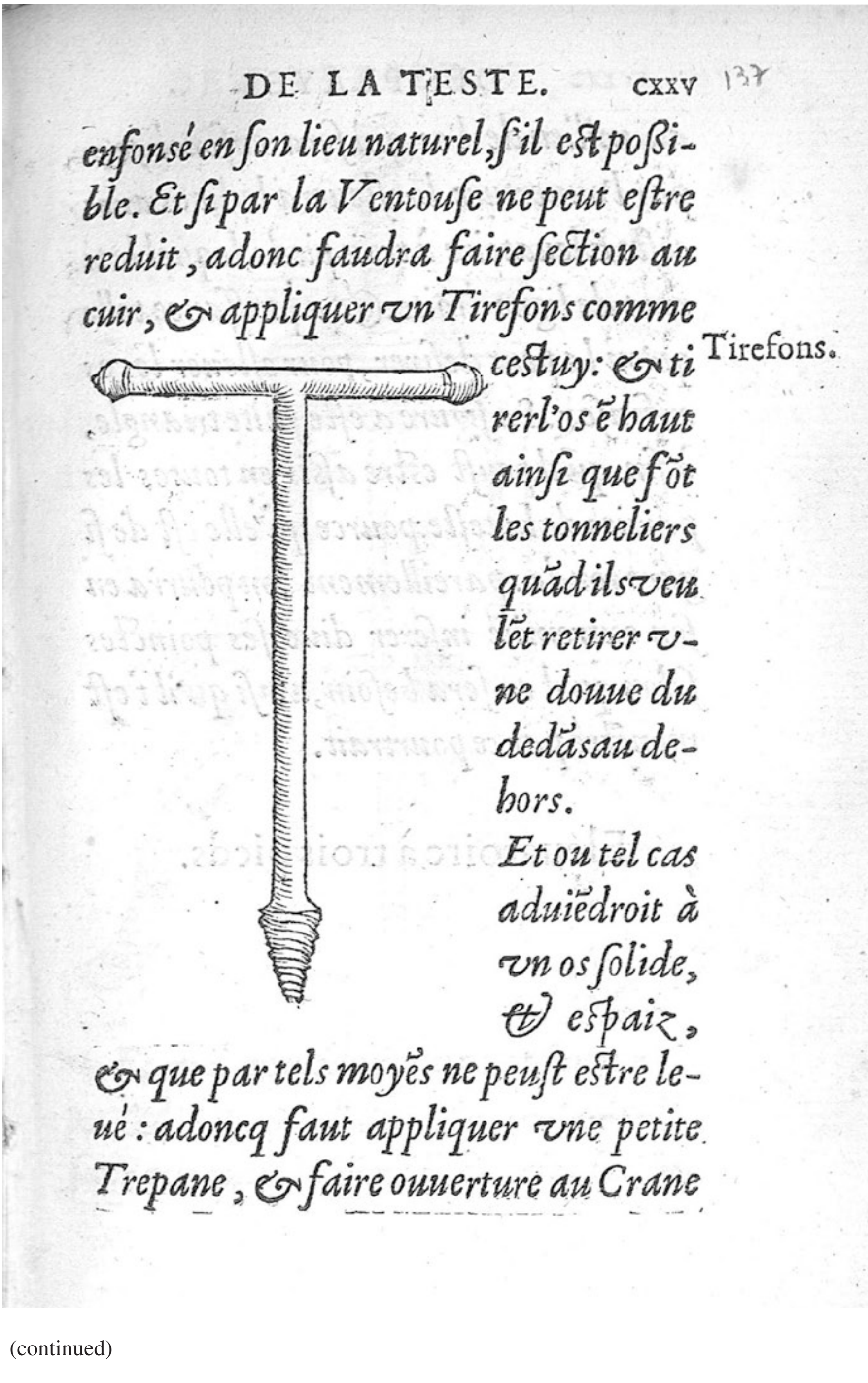

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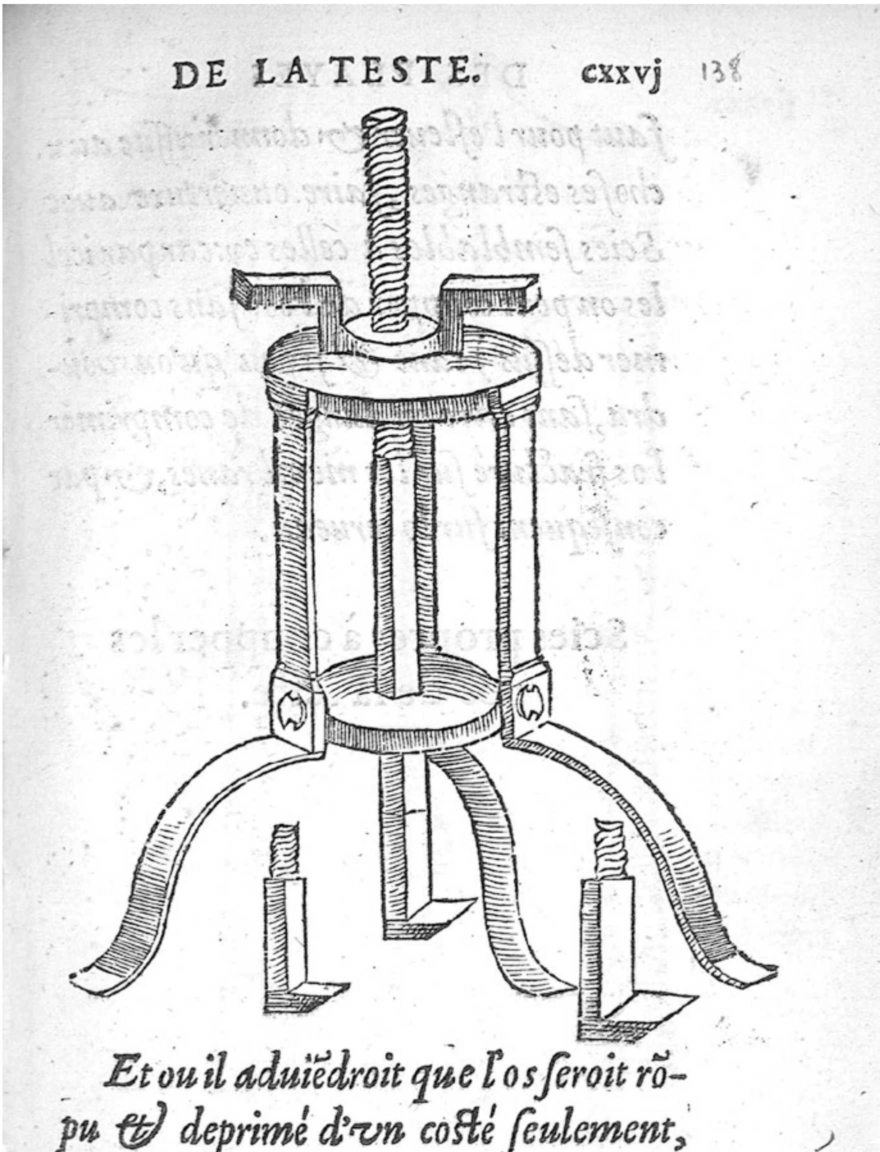
enfonsé en ſon lieu naturel, ſ'il eſt poßible. Et ſi par la Ventouſe ne peut eſtre reduit, adonc faudra faire ſection au cuir, & appliquer vn Tireſons comme ceſtuy: & tirer l'os ẽ haut ainſi que fõt les tonneliers quãd ils veulẽt retirer vne doue du dedãs au dehors. Tirefons.

Et ou tel cas aduiẽdroit à vn os ſolide, & eſpaiz, & que par tels moyẽs ne peuſt eſtre leué: adoncq faut appliquer vne petite Trepane, & faire ouuerture au Crane

Fig. 13.1 (continued)



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*Et ou il aduiẽdroit que l'os ſeroit rõ-
pu & deprimé d'vn coſté ſeulement,
ſans que toute la piece fuſt enfonſee, il*

Fig. 13.1 (continued)

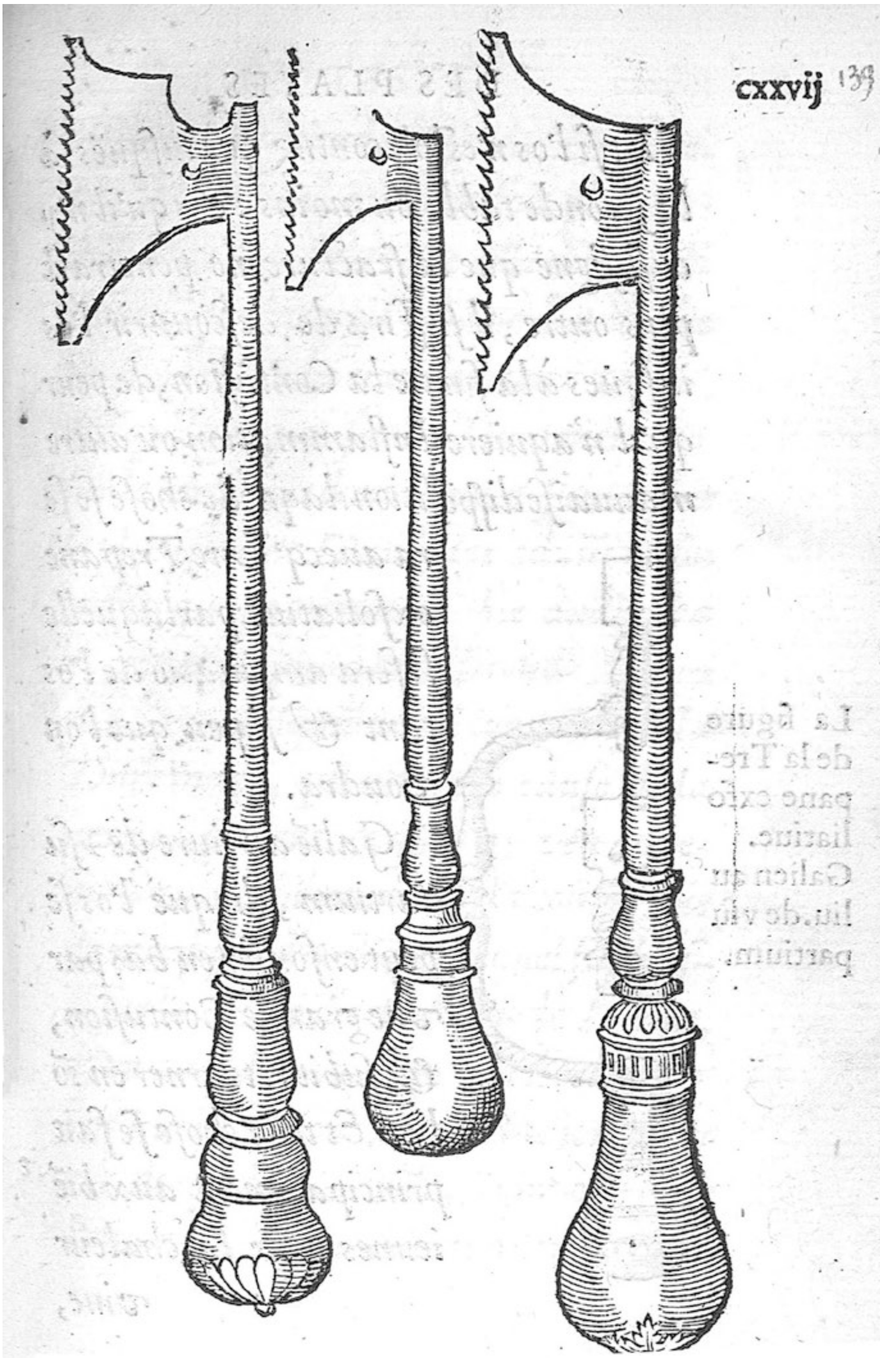
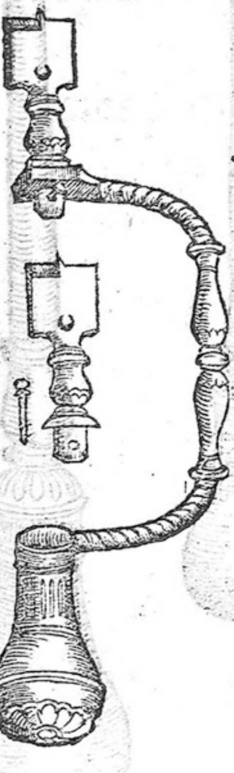


Fig. 13.1 (continued)

DES PLAYES

Et ſi l'os n'eſtoit contuz que iuſques à la ſeconde table, ou moins : & qu'il n'y euſt ſigne que la fracture ne penetraſt plus outre, il ſuffira de deſcouurir l'os iuſques à la fin de la Contuſion, de peur qu'il n'aquiere Inflammation ou autre mauuaiſe diſpoſition: laquelle choſe ſe fera auecq' vne Trepane exfoliatiue: par laquelle ſe fera amputatiõ de l'os tant & ſi peu que l'on voudra.

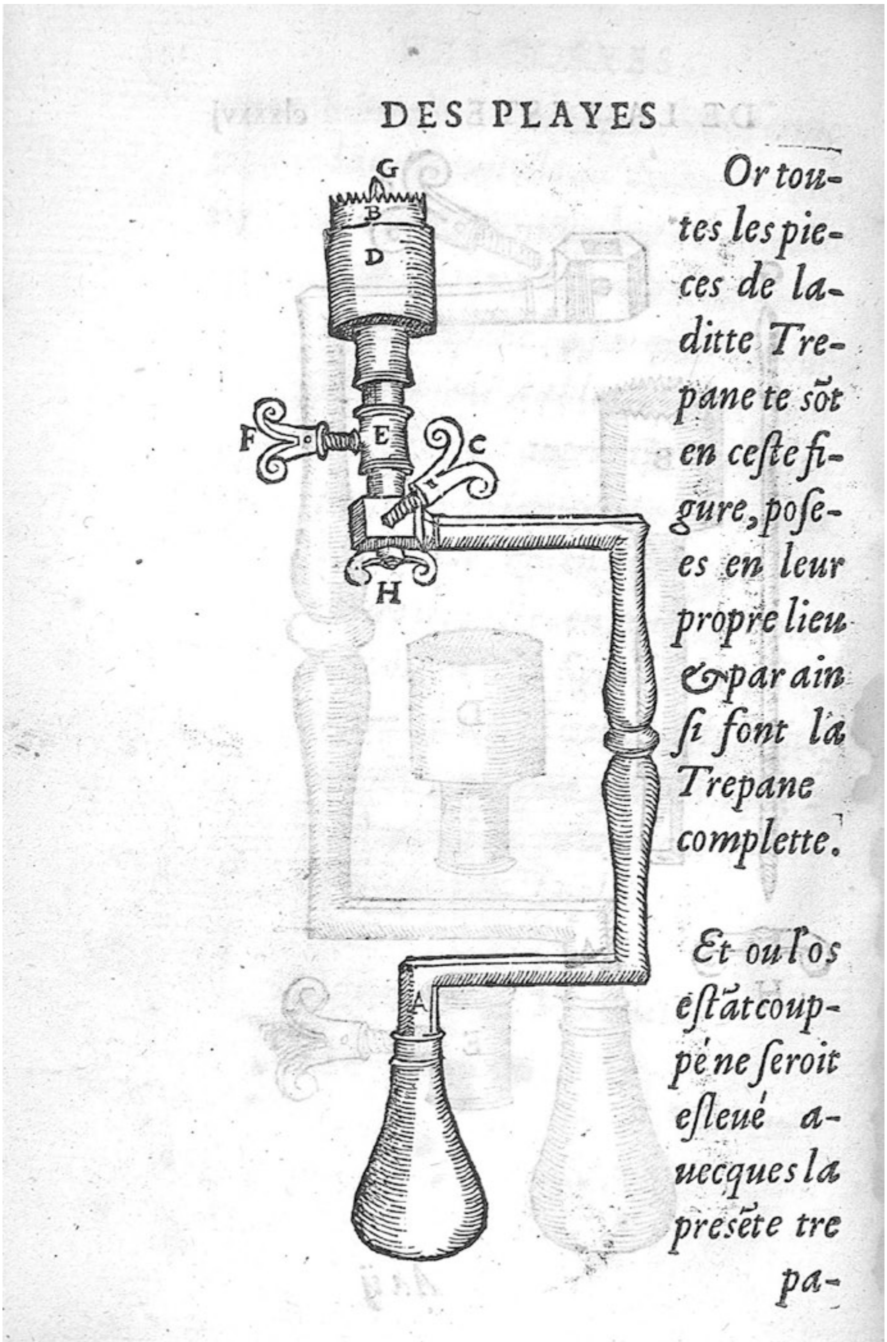


La figure de la Trepane exfoliatiue.

Galien au liu. de vſu partium.

Galiẽ au liure de vſu partium, dit que l'os ſe peut enfonſer en bas par vne grande Contuſion, & ſubit retourner en sõ lieu. Et telle choſe ſe fait principalement aux biẽ ieunes pour la chaleur viue,

Fig. 13.1 (continued)


DES PLAYES

Or tou-
tes les pie-
ces de la-
ditte Tre-
pane te sõt
en ceſte fi-
gure, poſe-
es en leur
propre lieu
& par ain
ſi font la
Trepane
complette.

Et ou l'os
eſtãt coup-
pé ne ſeroit
eſleué a-
uecques la
preſẽte tre
pa-

Fig. 13.1 (continued)

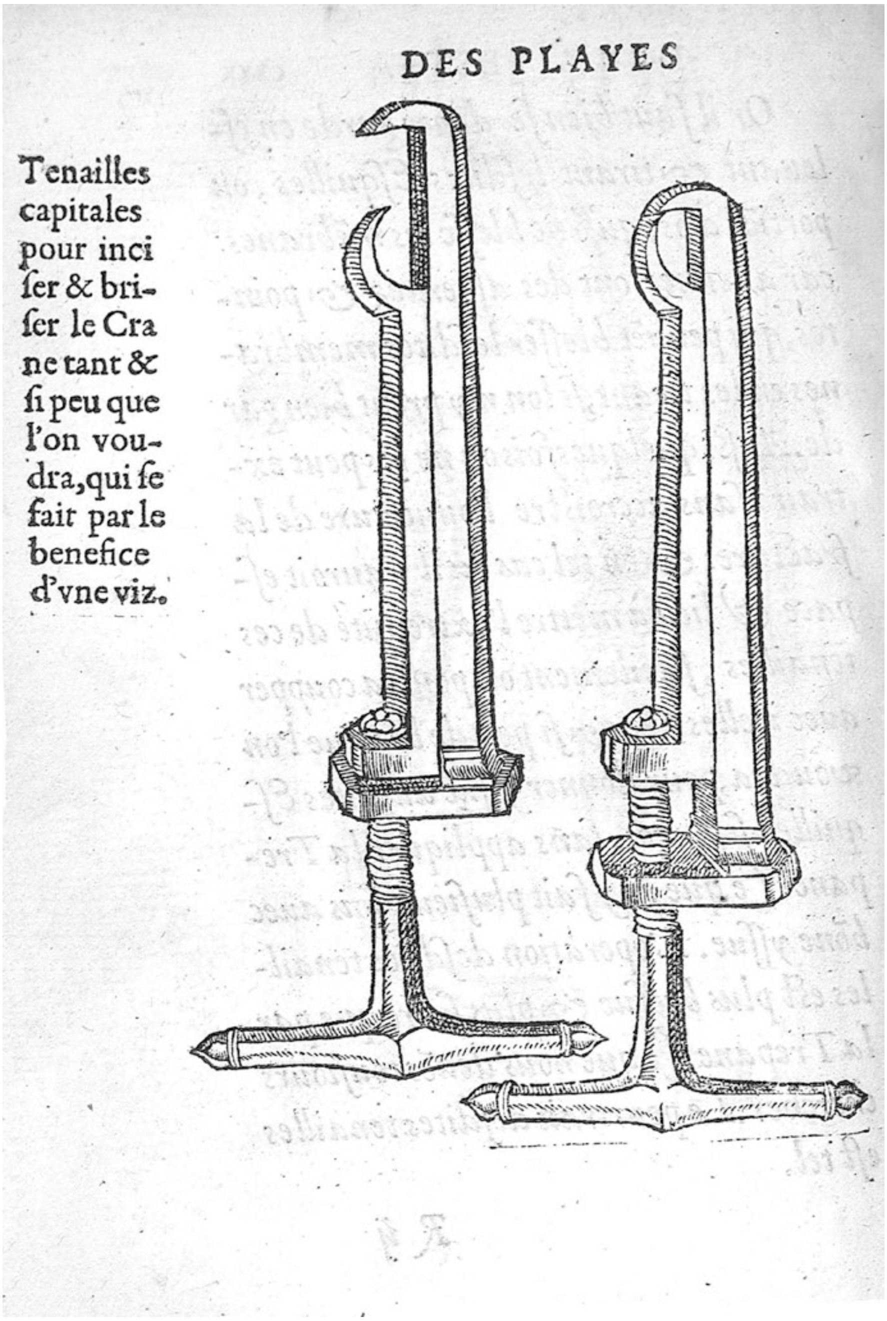
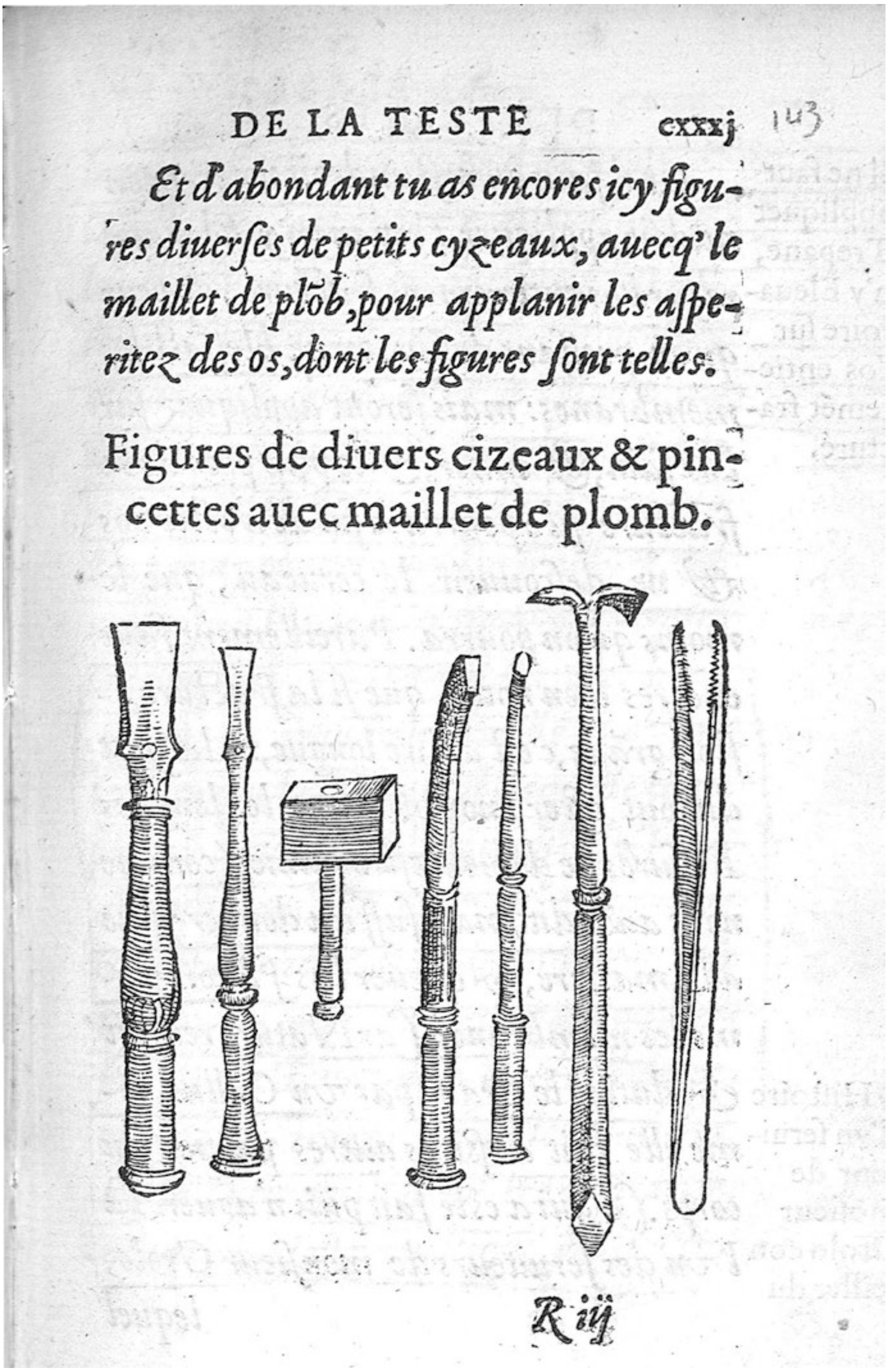


Fig. 13.1 (continued)

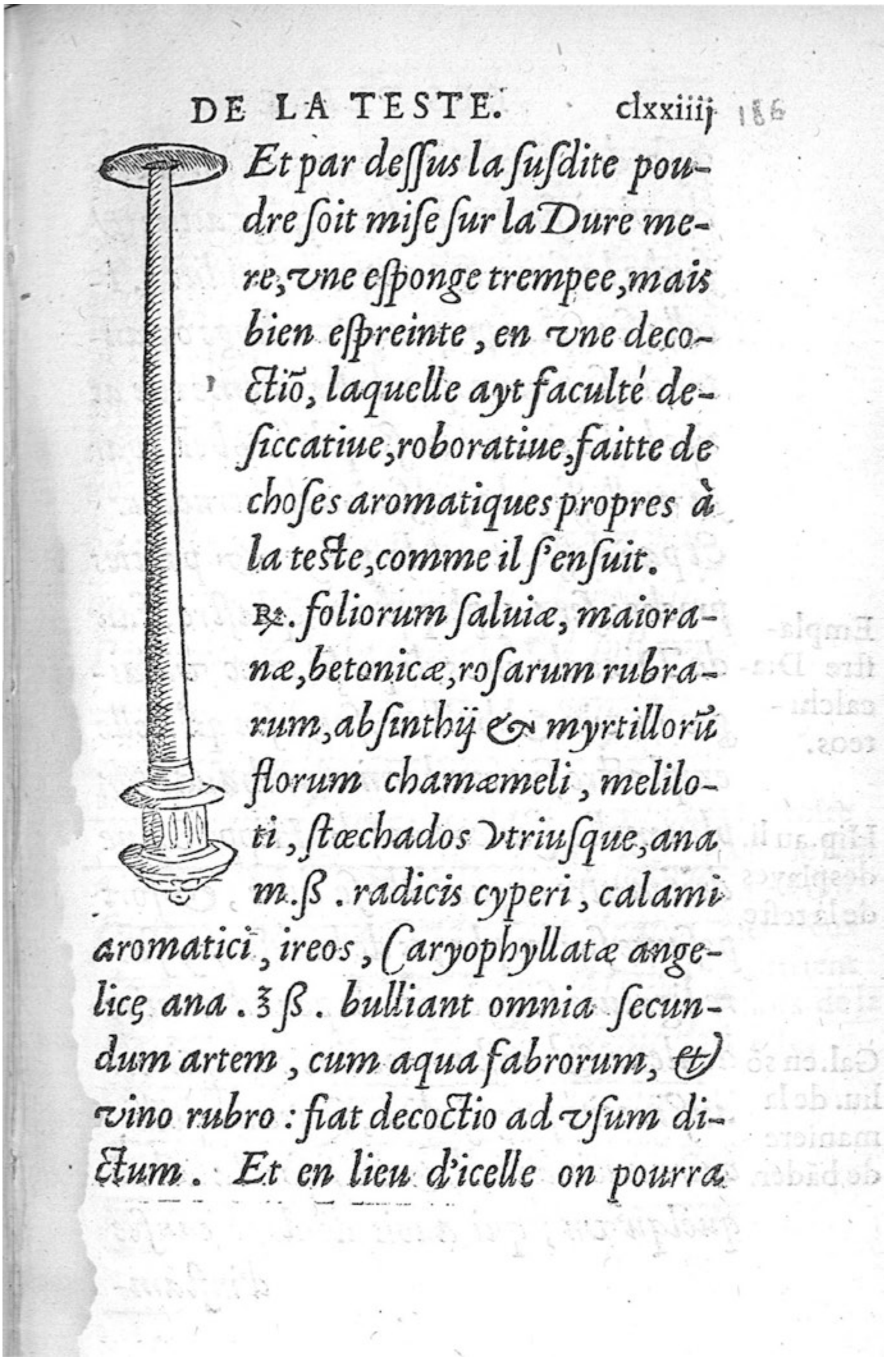

DE LA TESTE cxxxj

Et d'abondant tu as encores icy figures diuerses de petits cyzeaux, auecq' le maillet de plõb, pour applanir les asperitez des os, dont les figures sont telles.

Figures de diuers cizeaux & pincettes auec maillet de plomb.

R iij

Fig. 13.1 (continued)


DE LA TESTE. clxxiiij 186

Et par deſſus la ſuſdite pou-
dre ſoit miſe ſur la Dure me-
re, vne eſponge trempee, mais
bien eſpreinte, en vne deco-
ctiõ, laquelle ayt faculté de-
ſiccatiue, roboratiue, faitte de
choſes aromatiques propres à
la teſte, comme il ſ'enſuit.
℞. foliorum ſaluiæ, maiora-
næ, betonicæ, roſarum rubra-
rum, abſinthij & myrtillorũ
florum chamæmeli, melilo-
ti, ſtœchados vtriuſque, ana
m. ß. radicis cyperi, calami
aromatici, ireos, Caryophyllatæ ange-
licę ana. ℥ ß. bulliant omnia ſecun-
dum artem, cum aqua fabrorum, &
vino rubro: fiat decoctio ad vſum di-
ctum. Et en lieu d'icelle on pourra

Fig. 13.1 (continued)

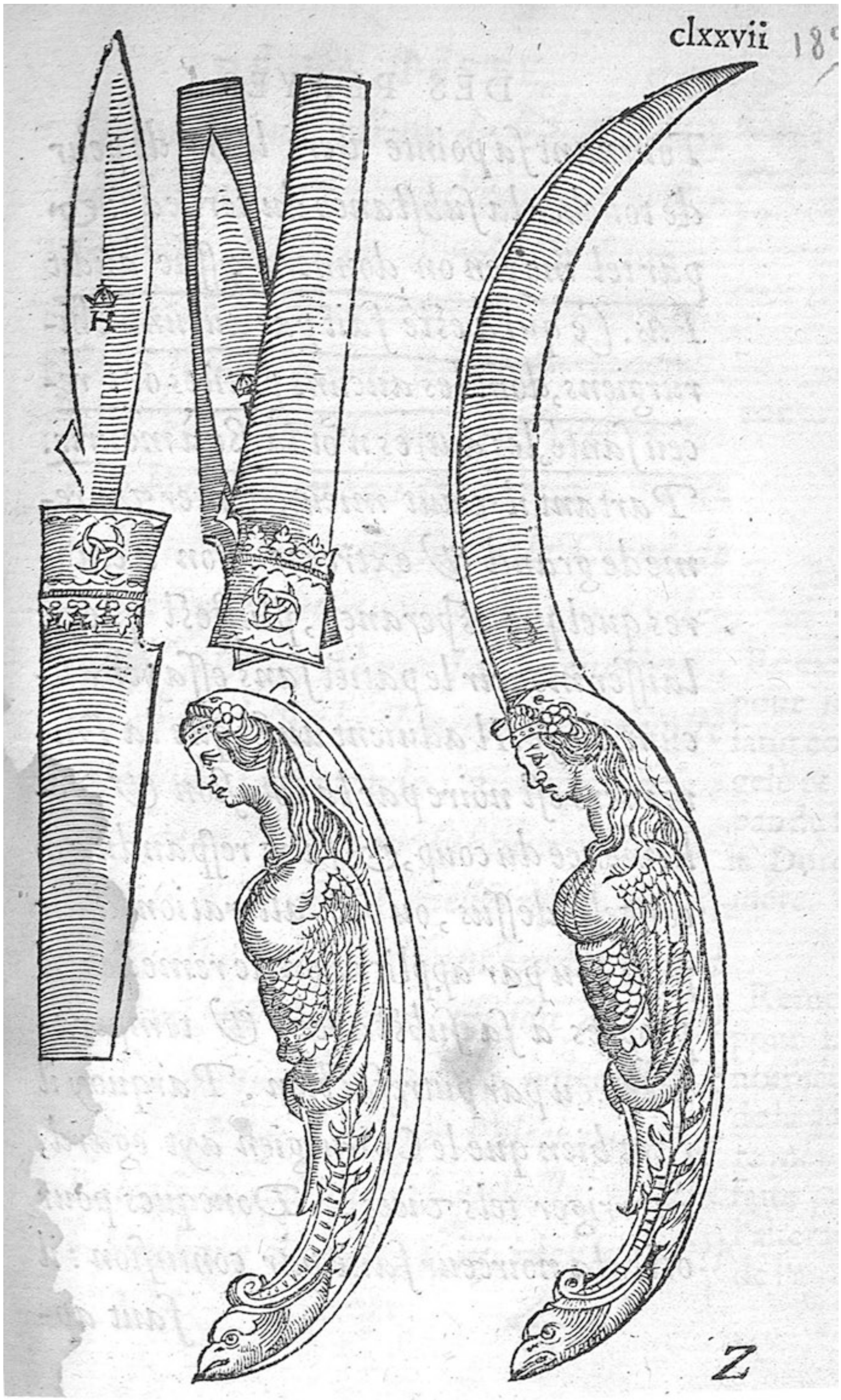


Fig. 13.1 (continued)

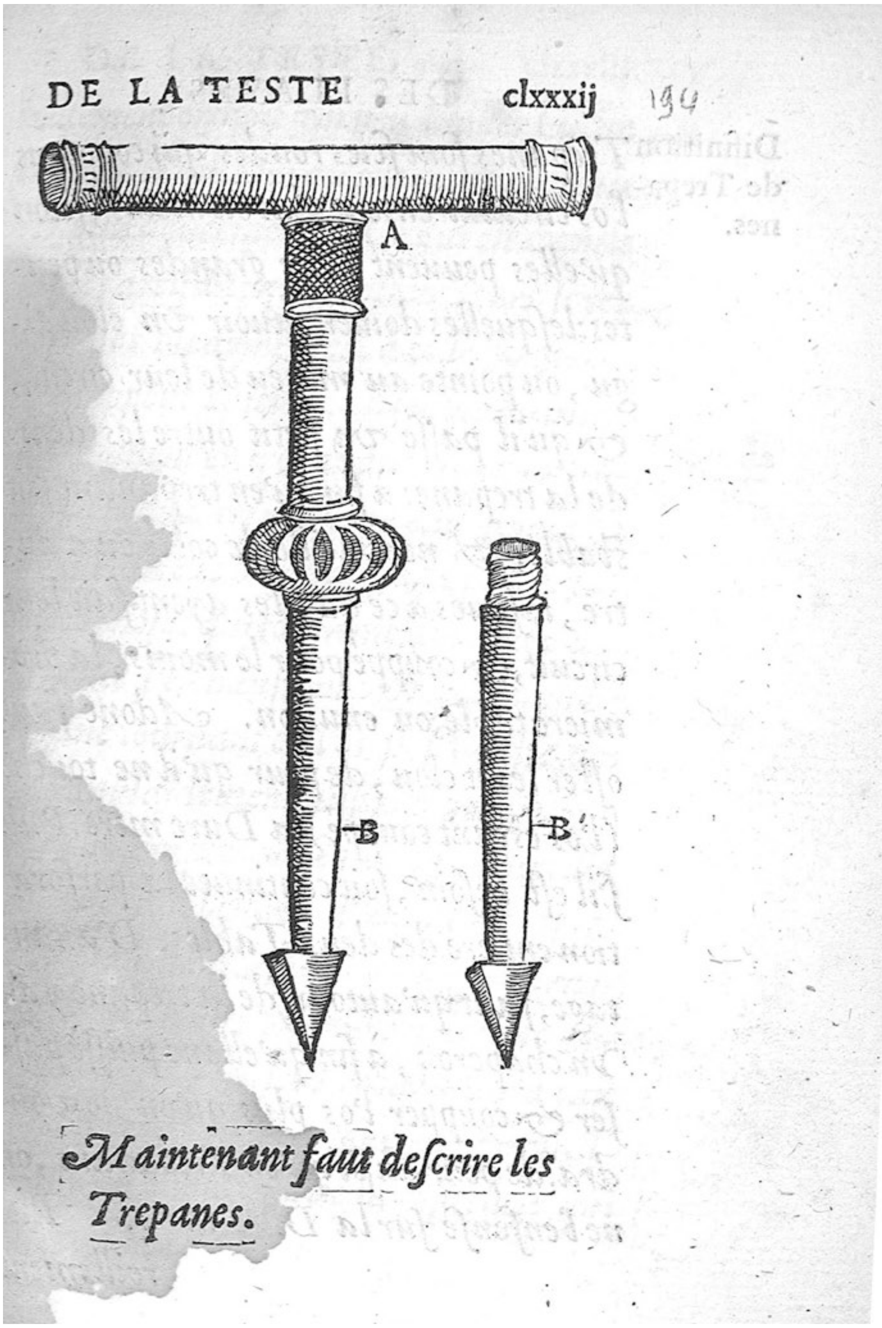


Fig. 13.1 (continued)

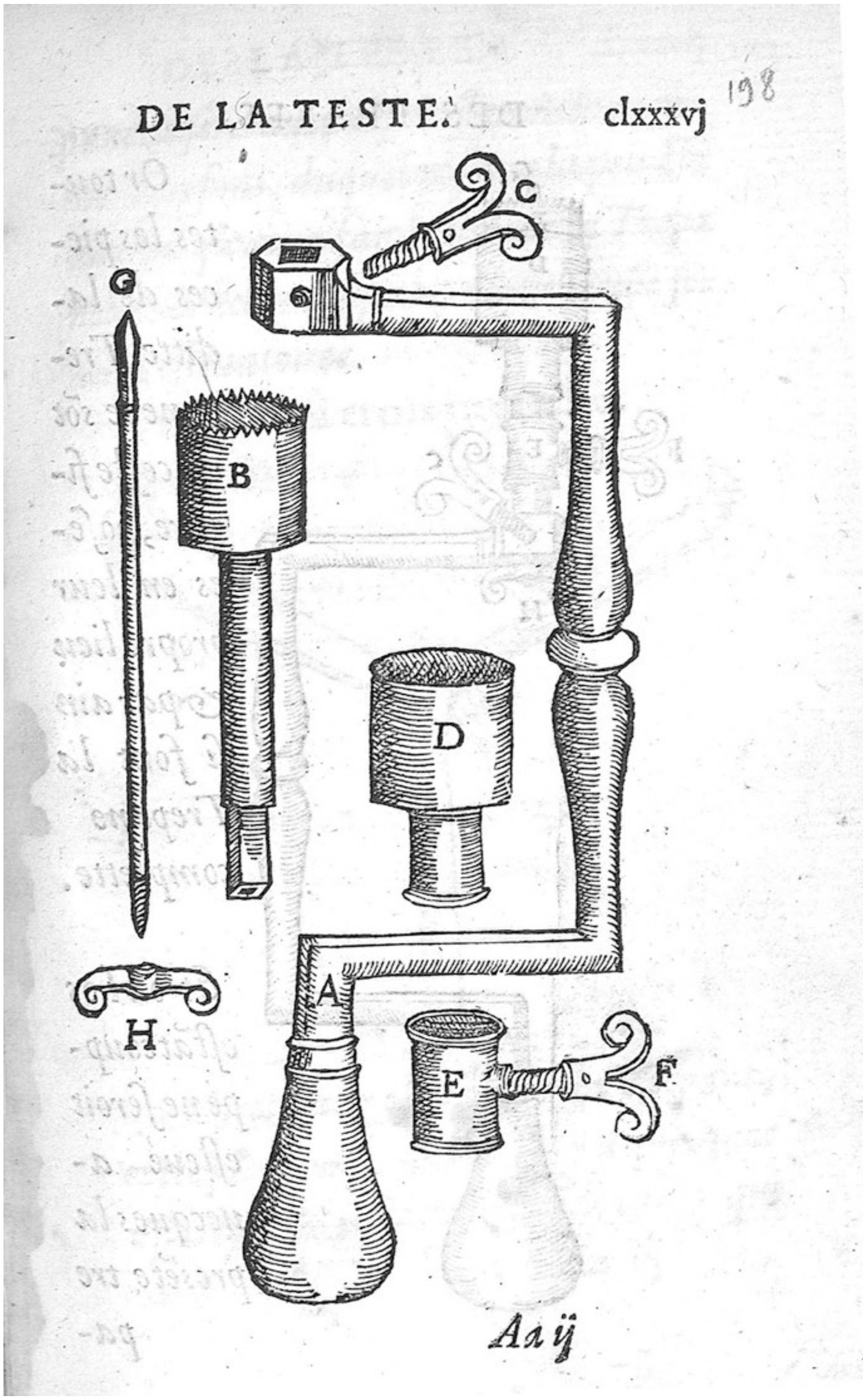
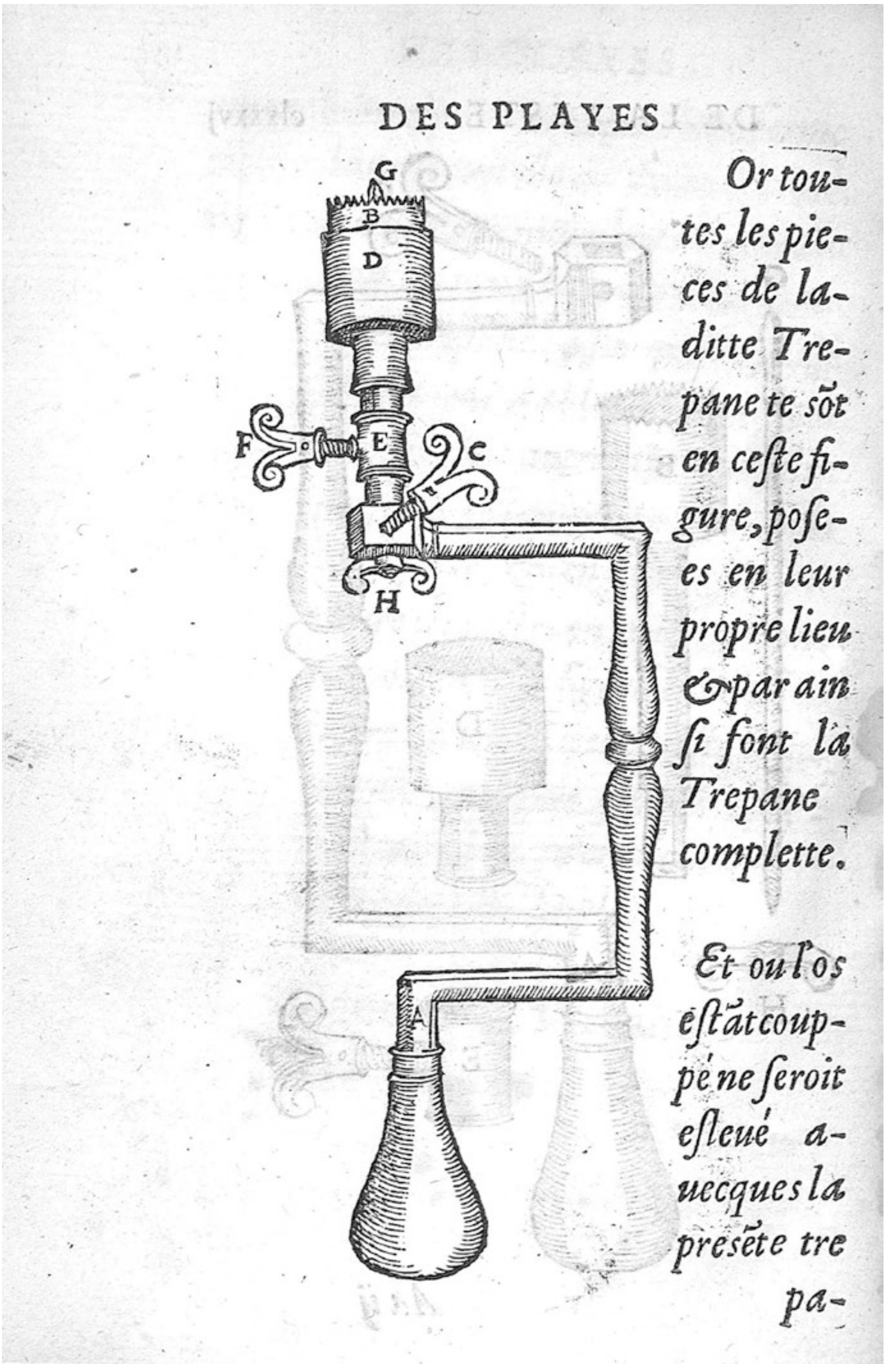


Fig. 13.1 (continued)


DES PLAYES

Or toutes les pieces de laditte Trepane te sõt en ceſte figure, poſees en leur propre lieu & par ainſi font la Trepane complette.

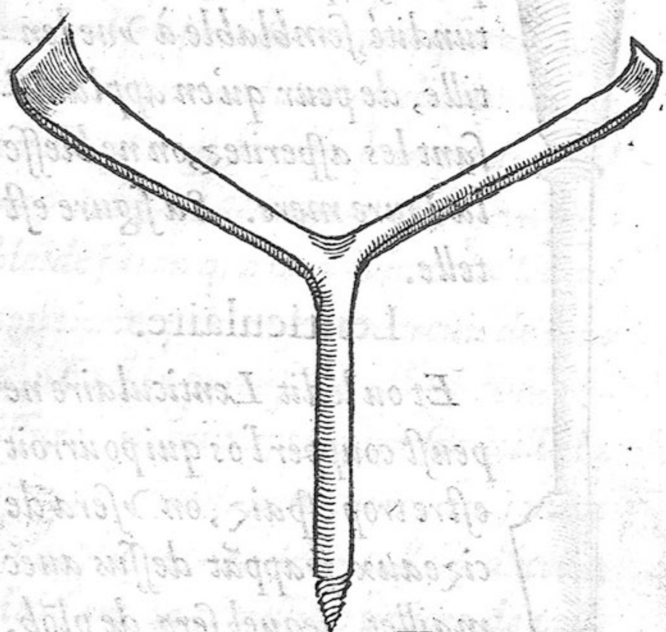
Et ou l'os eſtãt couppé ne ſeroit eſleué auecques la preſẽte trepa-

Fig. 13.1 (continued)

DE LA TESTE. clxxxvij 198

pane:le ſera auec ceſt inſtrument nommé Tirefons, duquel poſeras la poincte au trou qu'aura fait le clou de la Trepane:les brãches duquel peuuent außi ſeruir d'eſleuatoires.

Tirefons à trois branches.



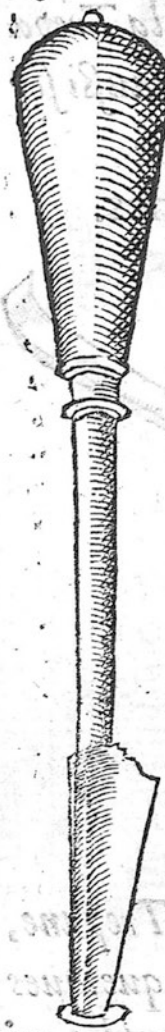
Apres auoir eſleué auec la Trepane, ceſte piece ronde de l'os, ſ'il y a quelques aſperitez du reſte en la ſecõde table qui

Aa iij

Fig. 13.1 (continued)

DES PLAYES

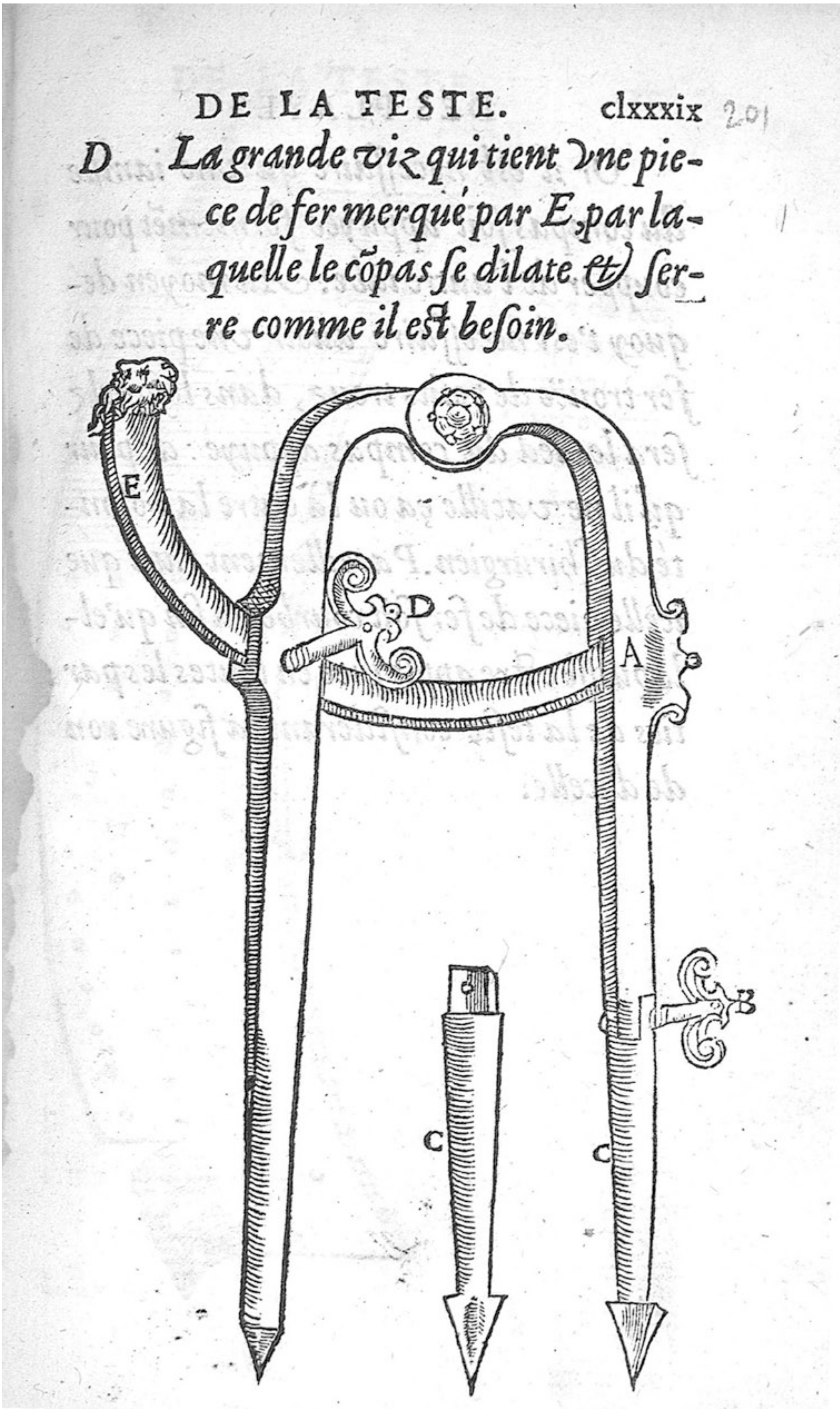
pourroiẽt bleſſer la Dure mere, lors qu'el
le fait ſon mouuemẽt: il les faut coupper
& applanir auec vn inſtru-
mẽt nommé Lenticulaire: le-
quel eſt ainſi nommé, pource
qu'en ſa poincte y a vne ro-
tundité, ſemblable à vne len-
tille, de peur qu'en applaniſ-
ſant les aſperitez, on ne bleſſe
la Dure mere. Sa figure eſt
telle.



Lenticulaire.

Et ou ledit Lenticulaire ne
peuſt coupper l'os qui pourroit
eſtre trop eſpaiz, on vſera de
cizeaux, frappãt deſſus auec
maillet, lequel ſera de plõb,
de peur d'eſtonner le cerueau
que le moins qu'il ſera poſſi-
ble. Et ſeront oſtees les eſquilles & pe-
tits frag-

Fig. 13.1 (continued)


DE LA TESTE. clxxxix

D La grande viz qui tient vne piece de fer merqué par E, par laquelle le cõpas se dilate & serre comme il est besoin.

Fig. 13.1 (continued)

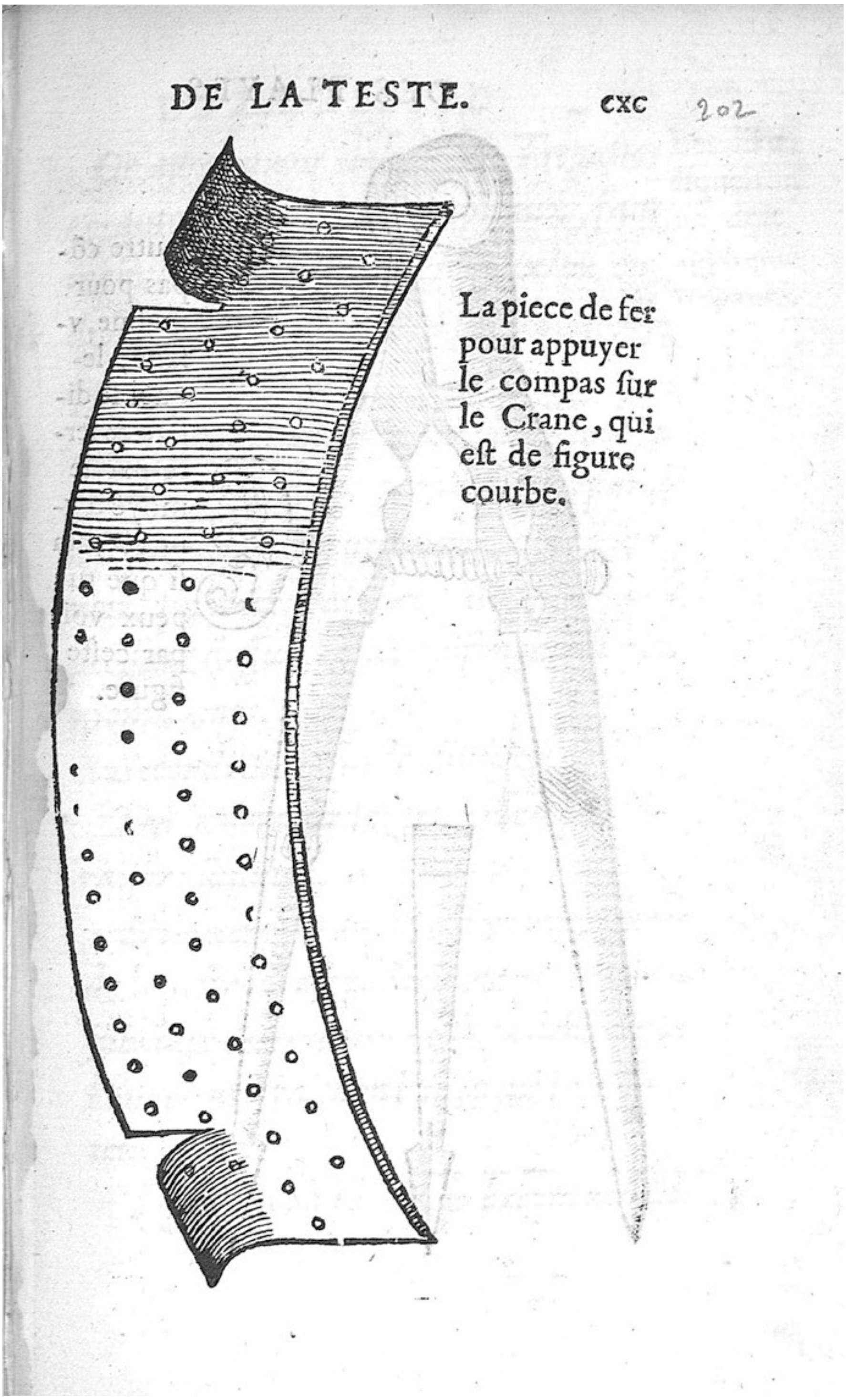


Fig. 13.1 (continued)

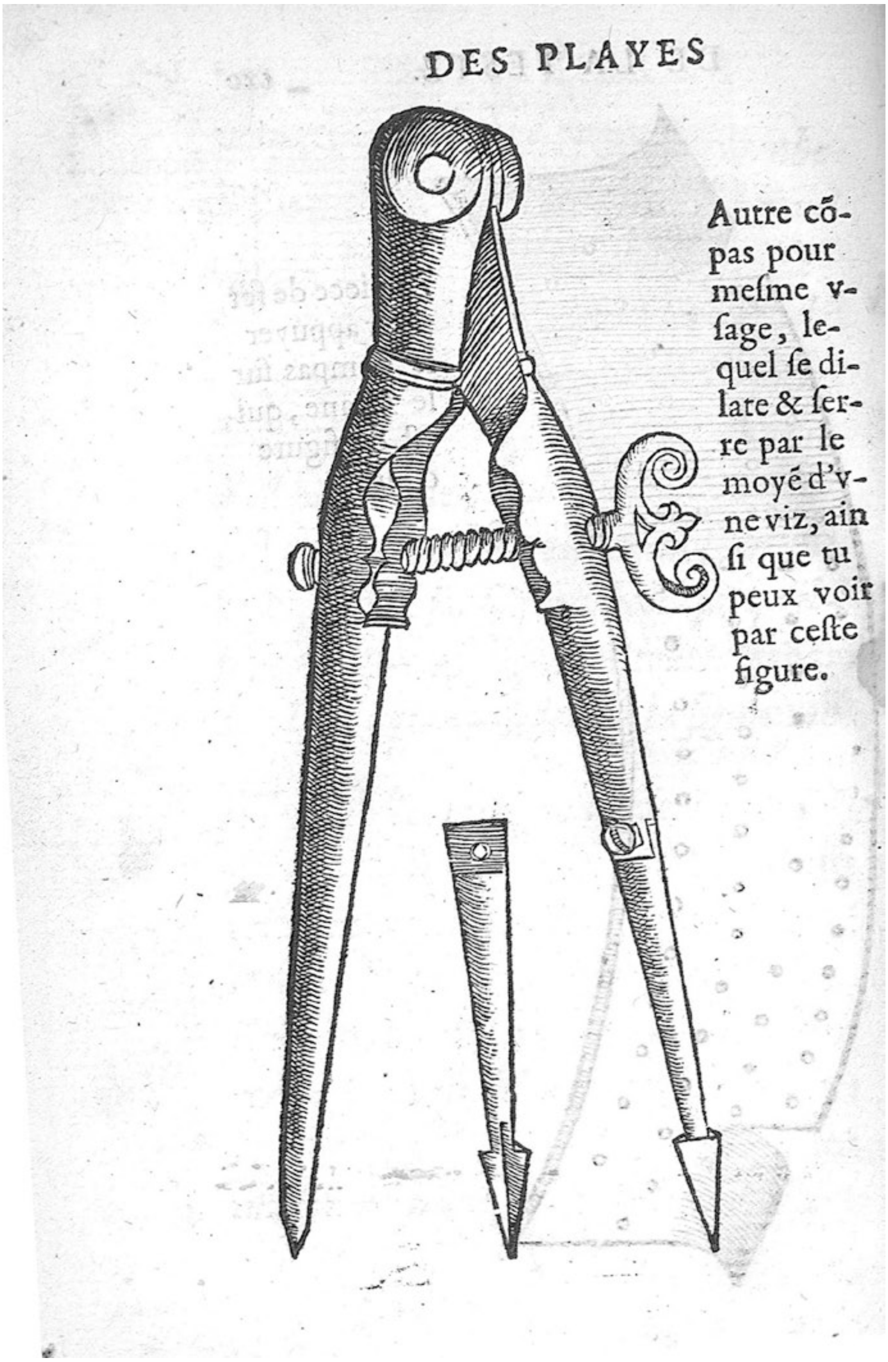


Fig. 13.1 (continued)

DE LA TESTE. cxciiij 206

des fuſt par la grace de dieu, biẽ guary.

Tente de plomb cannulee, de figure platte, pour donner yſſue à la ſanie retenuë entre le Crane & la Dure mere.

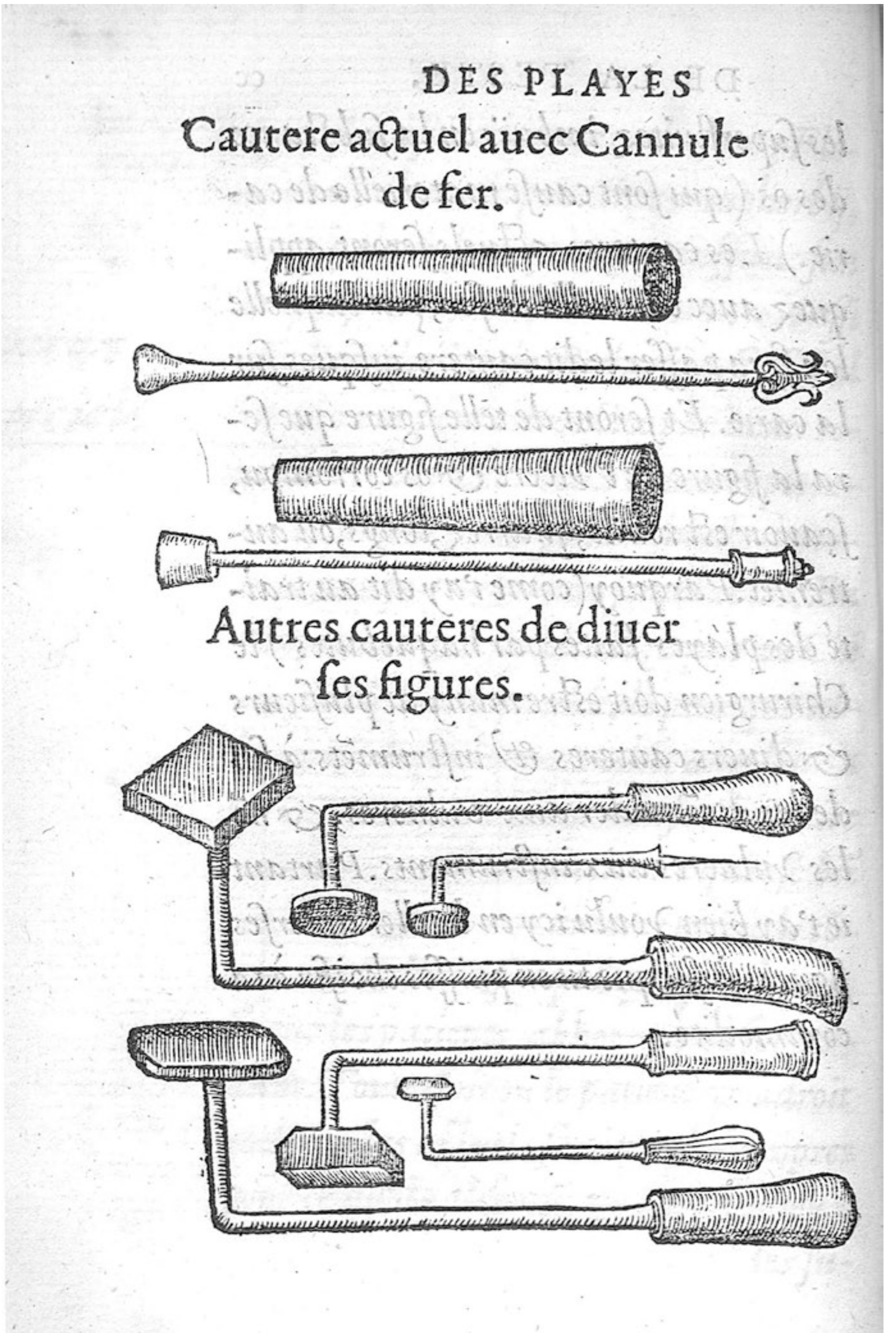
Syringue.

Hiſtoire de monſieur de Pienne.

Autre hiſtoire preſque ſemblable, que ie veis au ſiege de Mets, de monſieur de Pienne nommé àlors Bugueno: lequel eſtant ſur la breſche fut bleßé en la temple auec fracture d'os, par vn eſclat de pierre de la muraille, fait d'ũ coup de canon tiré par l'ennemy. Et ſubit qu'il fut frappé, tõba en terre, & ietta le ſang

Bb ij

Fig. 13.1 (continued)

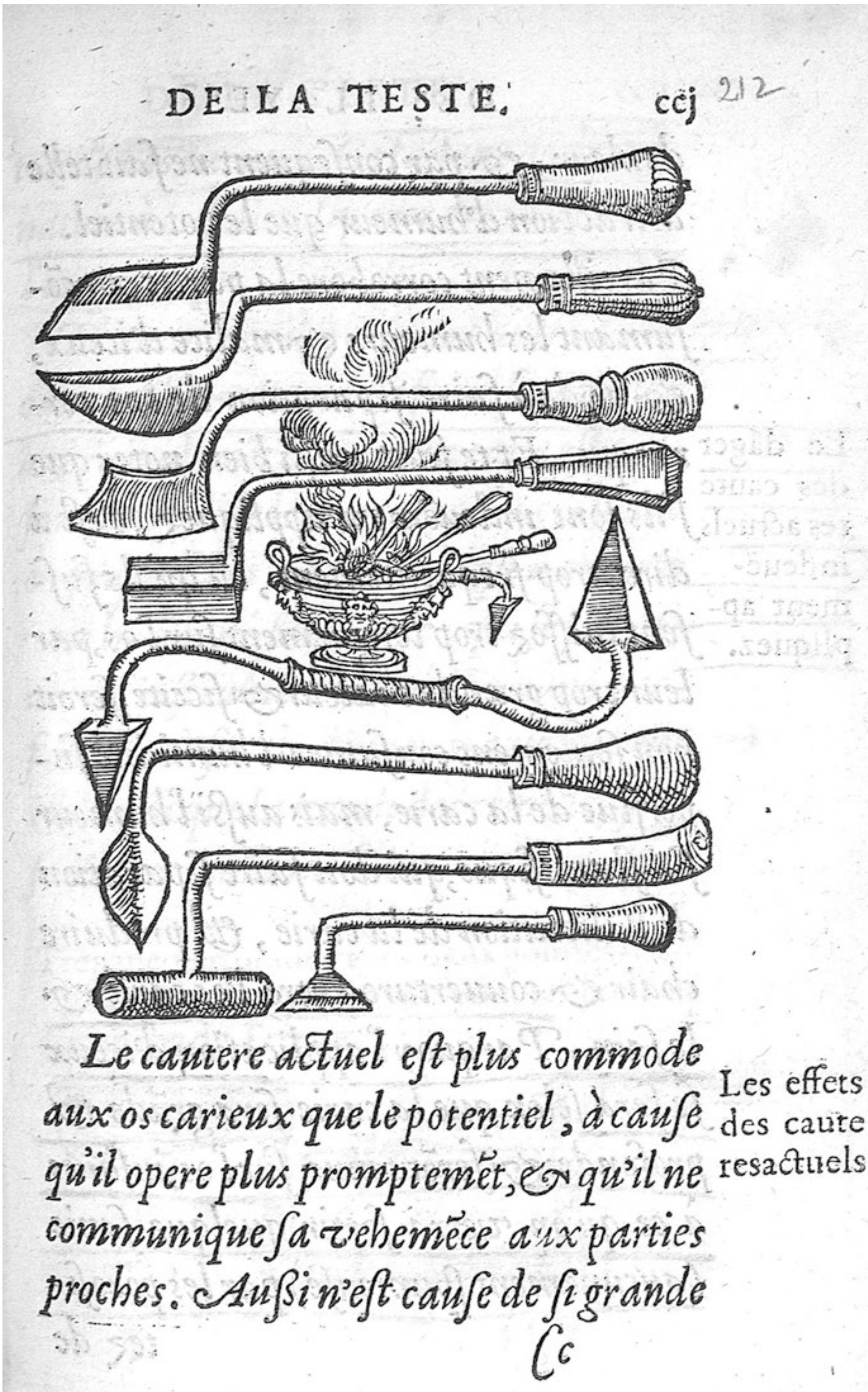


DES PLAYES

Cautere actuel auec Cannule de fer.

Autres cauteres de diuerses figures.

Fig. 13.1 (continued)



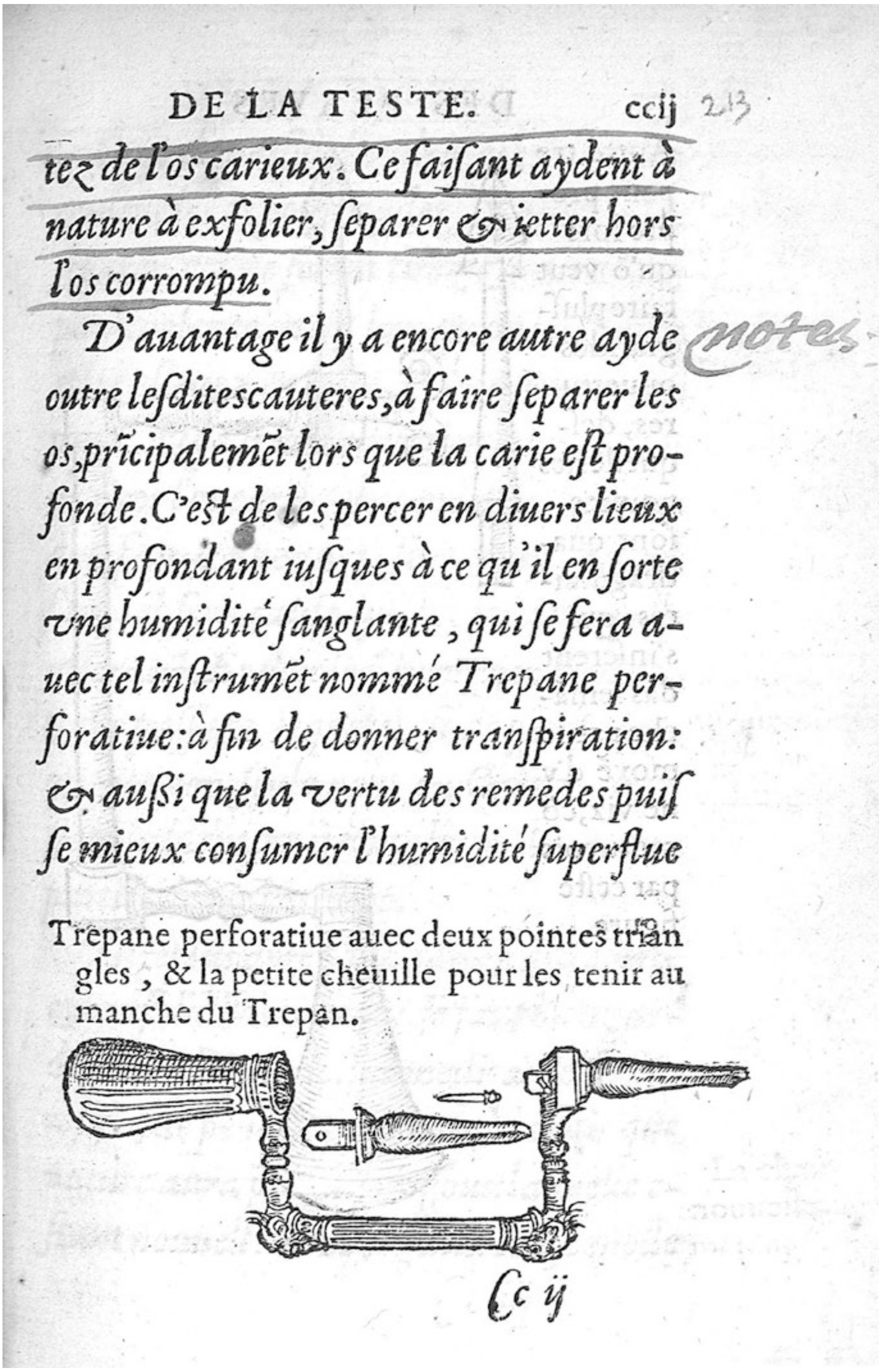
DE LA TESTE. ccj 212

Le cautere actuel eſt plus commode aux os carieux que le potentiel, à cauſe qu'il opere plus promptemẽt, & qu'il ne communique ſa vehemẽce aux parties proches. Außi n'eſt cauſe de ſi grande

Les effets des caute resactuels

Cc

Fig. 13.1 (continued)


DE LA TESTE. ccij

tez de l'os carieux. Ce faiſant aydent à nature à exfolier, ſeparer & ietter hors l'os corrompu.

D'auantage il y a encore autre ayde outre leſdites cauteres, à faire ſeparer les os, prĩcipalemẽt lors que la carie eſt profonde. C'eſt de les percer en diuers lieux en profondant iuſques à ce qu'il en ſorte vne humidité ſanglante, qui ſe fera auec tel inſtrumẽt nommé Trepane perforatiue: à fin de donner tranſpiration: & auſſi que la vertu des remedes puiſſe mieux conſumer l'humidité ſuperflue

Trepane perforatiue auec deux pointes triangles, & la petite cheuille pour les tenir au manche du Trepan.

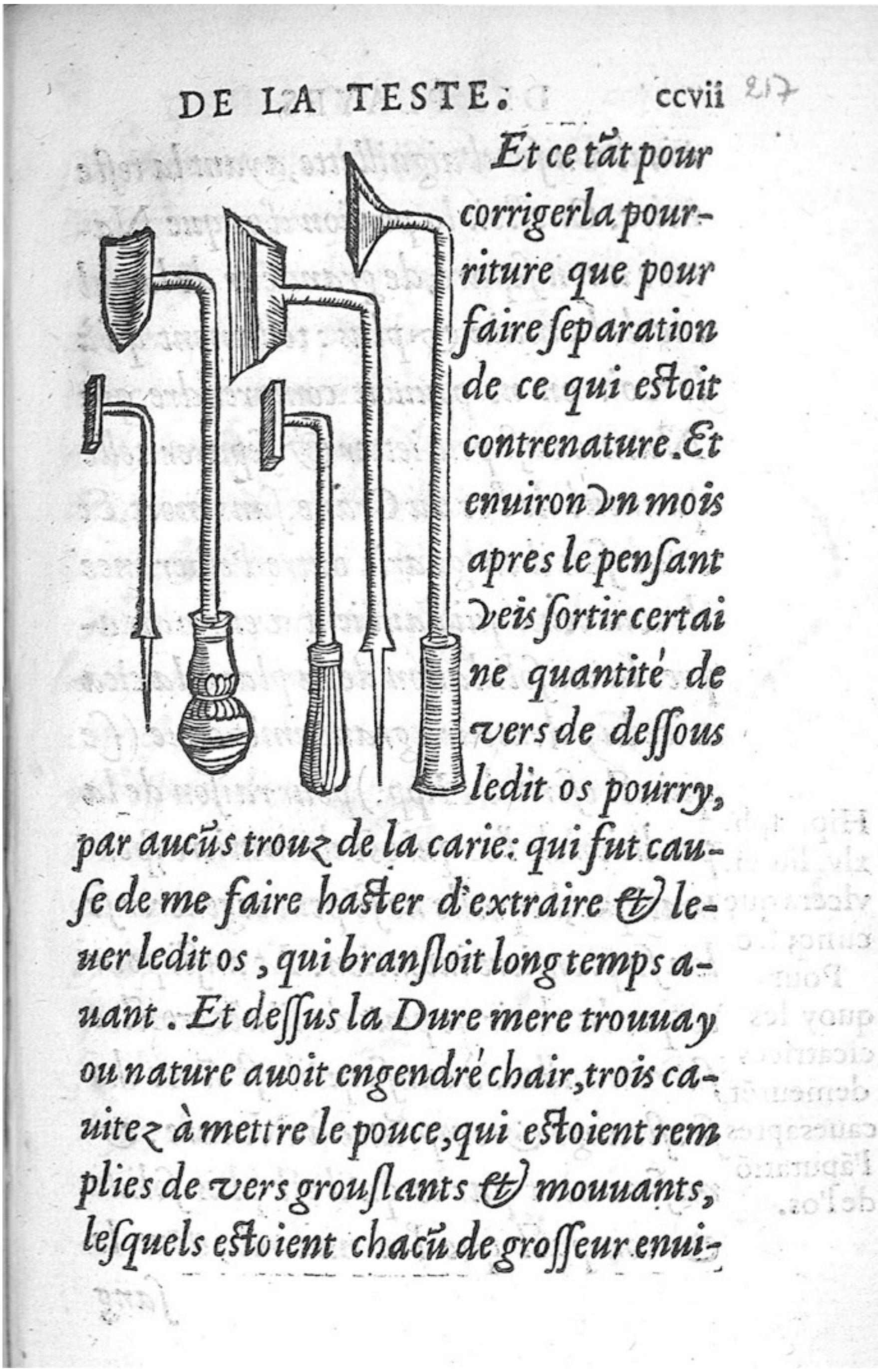
Cc ij

Fig. 13.1 (continued)

DES PLAYES

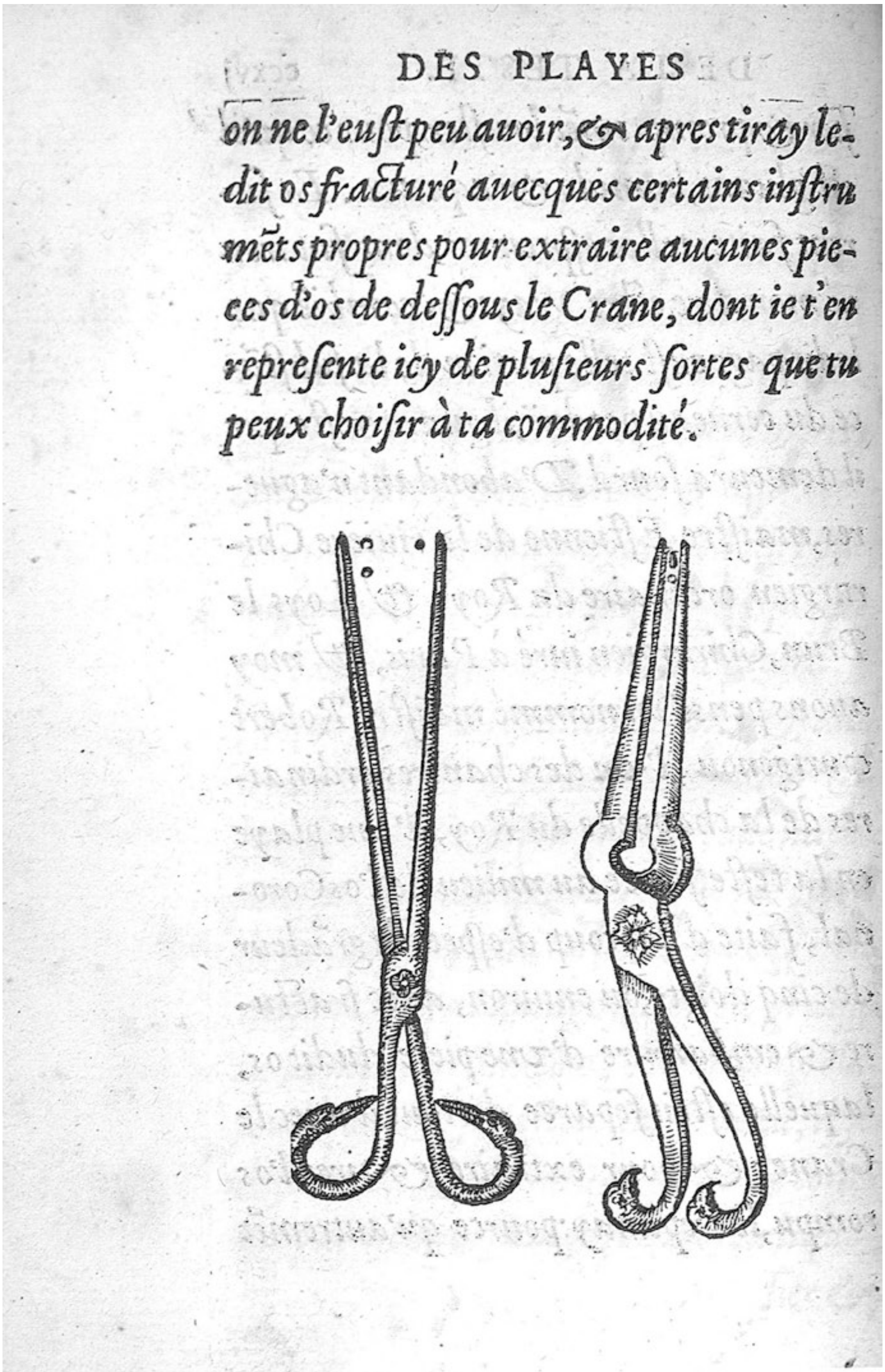
Autre tre
pane pro-
pre lors
qu'ō veut
faire pluſ-
grandes
ouuertu-
res, deſ-
quellesles
pointes
ſont qua-
drāgulai-
res, qui
s'inſerent
dās lemā-
che par le
moyē d'v
ne viz, cō
me tu vois
par ceſte
figure.

Fig. 13.1 (continued)


DE LA TESTE. ccvii

Et ce tãt pour corrigerla pourriture que pour faire ſeparation de ce qui eſtoit contrenature. Et enuiron vn mois apres le penſant veis ſortir certaine quantité de vers de deſſous ledit os pourry, par aucũs trouz de la carie: qui fut cauſe de me faire haſter d'extraire & leuer ledit os, qui branſloit long temps auant. Et deſſus la Dure mere trouuay ou nature auoit engendré chair, trois cauitez à mettre le pouce, qui eſtoient remplies de vers grouſlants & mouuants, leſquels eſtoient chacũ de groſſeur enui-

Fig. 13.1 (continued)



DES PLAYES

on ne l'euſt peu auoir, & apres tiray le-dit os fracturé auecques certains inſtru mẽts propres pour extraire aucunes pie-ces d'os de deſſous le Crane, dont ie t'en repreſente icy de pluſieurs ſortes que tu peux choiſir à ta commodité.

Fig. 13.1 (continued)

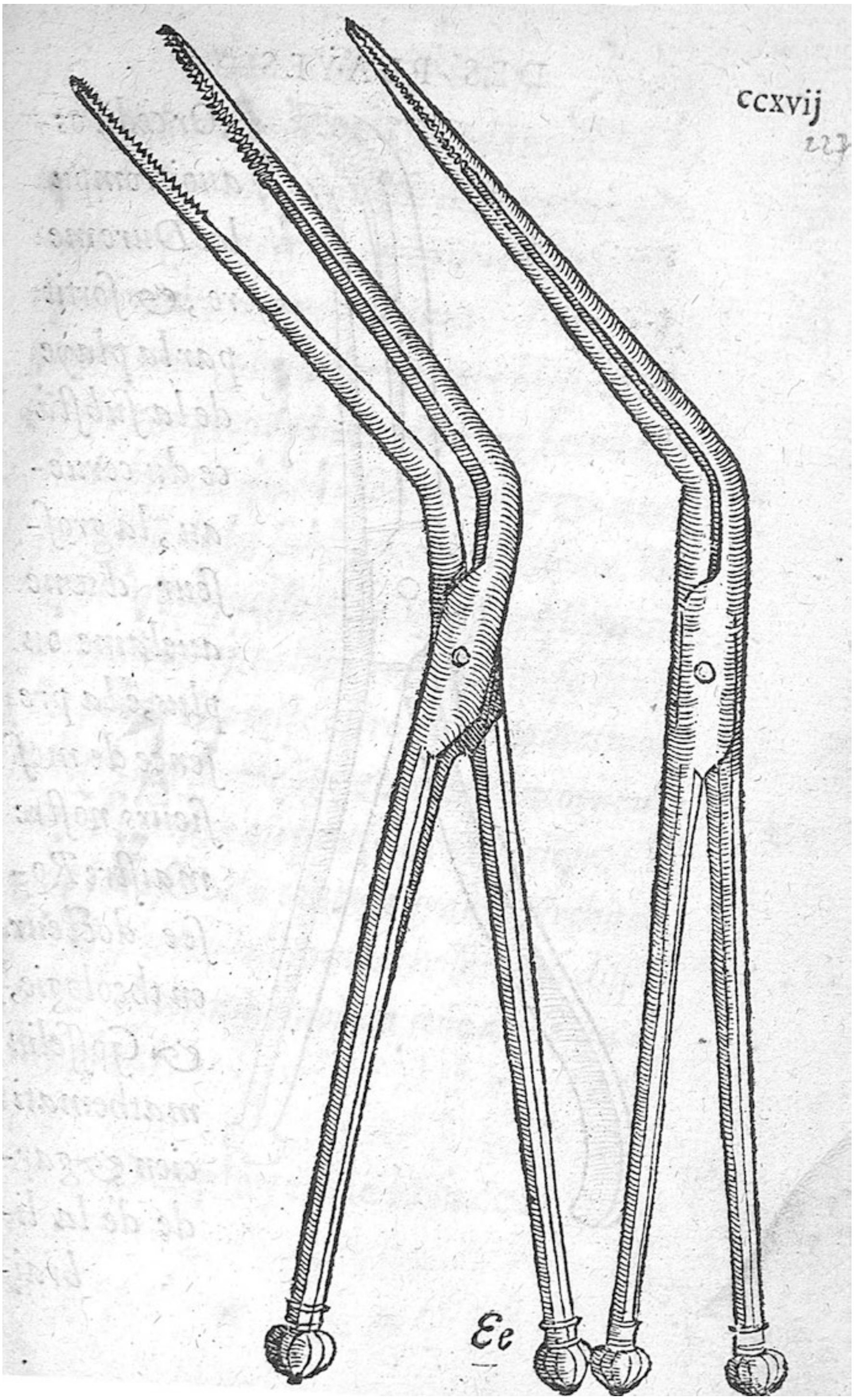


Fig. 13.1 (continued)

by tapping perpendicular to its axis with a heavy-lead hammer. A particular type of trepanation instrument that was well described by Paré was similar to a compass, with a central support point and a cutting point that cuts the bone as it spins. He used a bent metal template with holes that could be adapted to the head in order to lean the compass safely. The size of the drill was determined by slewing range, which could be adjusted by means of a screw placed between both axes of the compass. This instrument was not very popular later.

The trepanation technique described by Paré strictly follows Hippocrates' recommendations, including, for example, the use of oil to lubricate the cut or cool the trephine, always taking into consideration not to harm the dura mater. The areas of the skull where trepanations were forbidden were the same ones that Hippocrates mentioned. However, he described a case in which he carried out a trepanation on the temporal area of a patient. He sectioned the temporal muscle, pointing out that he did it against Hippocrates' recommendations. However, he seemed to justify it as he mentioned that it was a special patient, particularly a nobleman from the court of king Henry, who had been injured with a stone over the Notre Dame bridge.

According to Paré, the trepanation intervention starts by adequately placing the patient's head on a support and plugging his or her ears with cotton. The bone is initially drilled with a sharp instrument that has a pyramid-shaped tip (*'foret'*). Then, a crown trepan with a stabilising central pin (*'la trepane'*) inserted in the initial hole is used and the bone is cut until reaching the dura mater. The cutting crown has a cap around it to adjust the cutting depth. To improve its use, it is lubricated with oil and cooled with water. Once the drill is complete, the disc of bone is removed with the *'tirefons'*. If there are unevennesses on the margins of the perforation, they can be removed with the chisel and the mallet or with the *'lenticulaire'*. If the fracture involves a suture, he recommends to trepan on both sides or use de-trepanning compass. The dura mater is not open and once the trepanation is complete different pastes and fillings that will be changed the following days are applied.

Paré's indications of trepanations in cranial fractures included lifting bone fragments, draining the blood accumulated between both layers of the bone, avoiding the consequences derived from the brain compression or when applicable cleaning and dressing the wound. Paré forbade the trepanation in the following situations: on free bone fragments as they could dip in the brain, on cranial sutures, over the eyebrows as it was possible to invade the frontal sinus which was filled with air and mucus, on decline areas of the head as the brain could be herniated due to its own weight, over bregma or anterior fontanelle in children, on the temporal area or temple as it was believed that sectioning the temporal muscle caused contralateral convulsions.

In this book, *'Methode curative des playes et fractures de la teste humaine'*, Paré not only describes but also draws the instruments used for trepanation. The drawings appear inserted in the text, without numeration or figure captions, being explained throughout it. Figure 13.1 reproduces the figures of the text that illustrate the instruments used for trepanation. The figures are identified by the page where they appear and the name given by the author. Below, we freely translate and summarise the relative to each one of them that appears in the text in relation to its use during trepanation.

– Page CXX: *'Rasoir pour faire la incision'*. It is a knife to incise the soft tissues to the bone, after shaving the hair, in a triangle or cruciform incision of the appropriate size for trepanning.
– Reverse page CXX: *'Cizeau pour separer le pericrane'*. It is an elevator to peel the skull of soft tissues, since the application of the trepan on them produces pain. Once this is done, the wound is filled with lint and left until the next day.
– Page CXXIIJ: *'Rugines, ou raspatoires'*. After discovering the wound again, a mixture of ink and some rose oil is applied so that it penetrates the bone only where it is fractured. To

locate this place, it is scratched with the *'rugines'* until the boundary between the area blackened by the ink and the white bone, where it can be perforated. The patient's mouth and nose are then closed and made to breathe out, and if bloody material comes out through the fissure, it can be affirmed that the internal and external table of the bone is fractured. With the *'rugines'* you can scrape the bone to the dura to release this material so that it does not get corrupted. Whenever it has been scraped or trepanned after the 7th or 10th day, either in summer or winter, most patients have died. However, 'I never leave patients without help and it is better to try any remedy, although questionable, than to do nothing'. The appropriate instruments to open the fissures are the *'rugines'*. Then Paré draws multiple interchangeable *'rugines'* that are screwed into a handle.

– Reverse page CXXIIJ: *'Rugines d'autre façon que les precedentes, pour couper d'avantage l'os'*.
– Page CXXV: *'Tirefond'*. Paré describes this instrument to treat sunken fractures in children when the application of a hot air cup through the skin fails. It is a T-shaped instrument with the end of the long stem ending in a thread like a screw, 'like that of the coopers', which is screwed into the bone to raise it through a small incision in the skin.
– Page CXXVJ: *'Elevatoire à trois pieds'*. In case of a more solid or thick bone, it is advisable to make a small trepan in the centre of sunken bone and lift the bone with this instrument, equipped with a hook that is inserted into the hole and with three support legs.
– Page CXXVIJ: *'Scies propres à coupper les os de la teste'*. Saws to complete the section of the bone that has not been fractured and, in this way, be able to raise it.
– Reverse page CXXVIJ: *'Trepane exfoliative'*. It is used to find bone contusions without apparent fracture, by removing the superficial layers of the bone, to release the blood between the two layers of the bone, the dura or the brain, or to remove splinters from the internal table that injure the dura mater or the brain, which are deadly often.
– Reverse page CXXIX: *'Elevatoires'*. They are used to remove bone fragments.
– Reverse page CXXX: *'Tenailles'*. It has the same purpose as elevators, but different mechanism. In both cases they are used to avoid trepanation, since the intervention is faster and safer.
– Page CXXXJ: *'Figures of divers cizeaux & pincettes avec maillet de plomb'*.
– Reverse page CLXXIIJ: *'Instrument prope pour presser & baisser la Dure mere en bas, à fin de donner issue à la sanie'*. It is a round, large and polished lenticular end instrument that is applied to the dura mater in order to release the blood or the effusions between the dura mater and the bone. To favour this, the patient's mouth and nose are closed and exhaled.
– Page CLXXVII: *'Lancette ou bistoire'*. Paré describes them in relation to the treatment of cerebral hernias through trepanations and that they cannot be resolved in any other way, and where the incision of the dura with one of these instruments is indicated to evacuate the underlying pus, without affecting the brain, and that in some patients makes them survive.
– Reverse page CLXXXJ: *'Foret por commencer à ouvrir le Crane'*. Drill with T-handle with pyramidal tip to start the trepanation, with the handle (A) and interchangeable tips with a screw for insertion in the handle (B, B′).
– Pages CLXXXVJ and reverse: *'Figure de la trepane'*. It shows the trepan with a brace handle and a crown driller disassembled and assembled. The instrument consists of the following parts: handle (A), trepan (B), clamping screw between both (C), cap (D) that avoids or prevents the trephine from penetrating more than what you want to reach, closing screw nut (E) that regulates the height of the cap and thus the depth of the trepanation, another closing screw (F), central pin that perforates until the diploe (G), and that is then extracted with this piece (H).

- Page CLXXXVIJ: *'Tirefond à trois branches'*. It serves to lift the bone disc, after screwing it into the central hole made with either the triangular perforator or the pin of the trephine.
- Reverse page CLXXXVIJ: *'Lenticulaire'*. The lenticular is a knife with the end protected by a lenticular widening that serves to regularise and cut the irregularities that remain in the bony edge of the internal table of the skull after trepanation, without injuring the dura mater. If there are large fragments, the pliers or the chisel must be used with the lead hammer.
- Page CLXXXIII: *'Compas pour couper l'os du Crane'*. It can be used as an alternative to trepan this compass that opens and closes with a screw. The pieces are compass foot (A), small screw that holds the tip (B), interchangeable cutting tips (C, C) and large screw that closes the piece (E) that allows the compass to open or close.
- Page CXC: *'Piece de fer pour appuyer le compas sur le Crane, qui est de figure courbe'*.
- Reverse page CXC. Another compass.
- Page CXCIIIJ: *'Tente de plomb cannulee, de figure platte, pou donner isue à la faine retenuë entre le Crane & la Dure mere'* and *'Syringue'*.
- Reverse page CC and CCJ: *'Cautere actuel avec cannule de fer'* and *'Autres cauteres de diverses figures'*. Cauteries of different forms. Those of iron cannulas will be for haemostasis of small bleeding points.
- CCIJ page: *'Trepane perforative'*. There is a trepan to pierce the skull, with a triangular tip and a small pin to hold the tip to the handle.
- Reverse page CCIJ: Another perforating trepan to make larger holes than the previous one.
- Page CCVII: Other flat cauteries to apply on complicated wounds.
- Reverse pages CCXVJ and CCVIJ: Clamps for extraction of projectiles and foreign bodies of wounds.

Jacques Guillemeau (1550–1584), who was a surgeon also born in France, described head wounds and skull fractures in his book *'La chirurgie françoise, recueillie des anciens Medecins et Chirurgiens avec plusieurs figures des Instrumens necesseres pour l'operation Manuelle'*, which was published in 1594 [2]. He basically followed the Hippocratic principles. He particularly recommended trepanning after the first 3 days with a warm weather. The trepanation can only be carried out during the first 2–3 days if the dura mater is affected. The areas of the skull where trepanations could be carried out were those allowed by Hippocrates. It was particularly contraindicated to trepan on sutures, fontanelles in children, on the lower areas of the skull particularly the temples to avoid the temporal muscles and over the eyebrows to avoid invading the frontal paranasal sinuses, which were described as a cavity *'pleine d'air & d'une humidité blanche'*.

He then described *'La manìere & method de bien trepaner'*. He recommended in first place to enlarge the wound by giving it the shape of an X or a T. The trepanation had several stages. First, the outer table was resected with a scrapper or an exfoliating trepan until the diploe was exposed. Then a drilling instrument aimed with a tip or pyramid was used to reach the dura mater. This is checked by using a lifter. Finally, the trepanation is completed with a truncated cone-shaped head that prevents the driller from dipping in the skull.

Guillemeau illustrates on pages 9 and 11 of his book the most important instruments of trepanation, drawn in two plates, with their description in separate pages (Fig. 13.2). Guillemeau indicates that he only shows the most comfortable and useful instruments. Most of the names of the anatomical elements, techniques and instruments are written in several languages, at least in French, Latin and Greek. It is remarkable that among the several surgical scenes that are depicted on the opening page of the book, the upper right represents a trepanation. The figures of the instruments related to trepanation are gathered in two plates that we describe below from the comments of the text written in French.

In the plate on page 9 the instruments are the following:

Fig. 13.2 Instruments related to the trepanation by Jacques Guillemeau (Guillemeau J. La chirurgie françoise, recueillie des anciens medecins et chirurgiens avec plusieurs figures des instrumens necesseres pour l'operation manuelle. Paris: Nicolas Gilles; 1594)

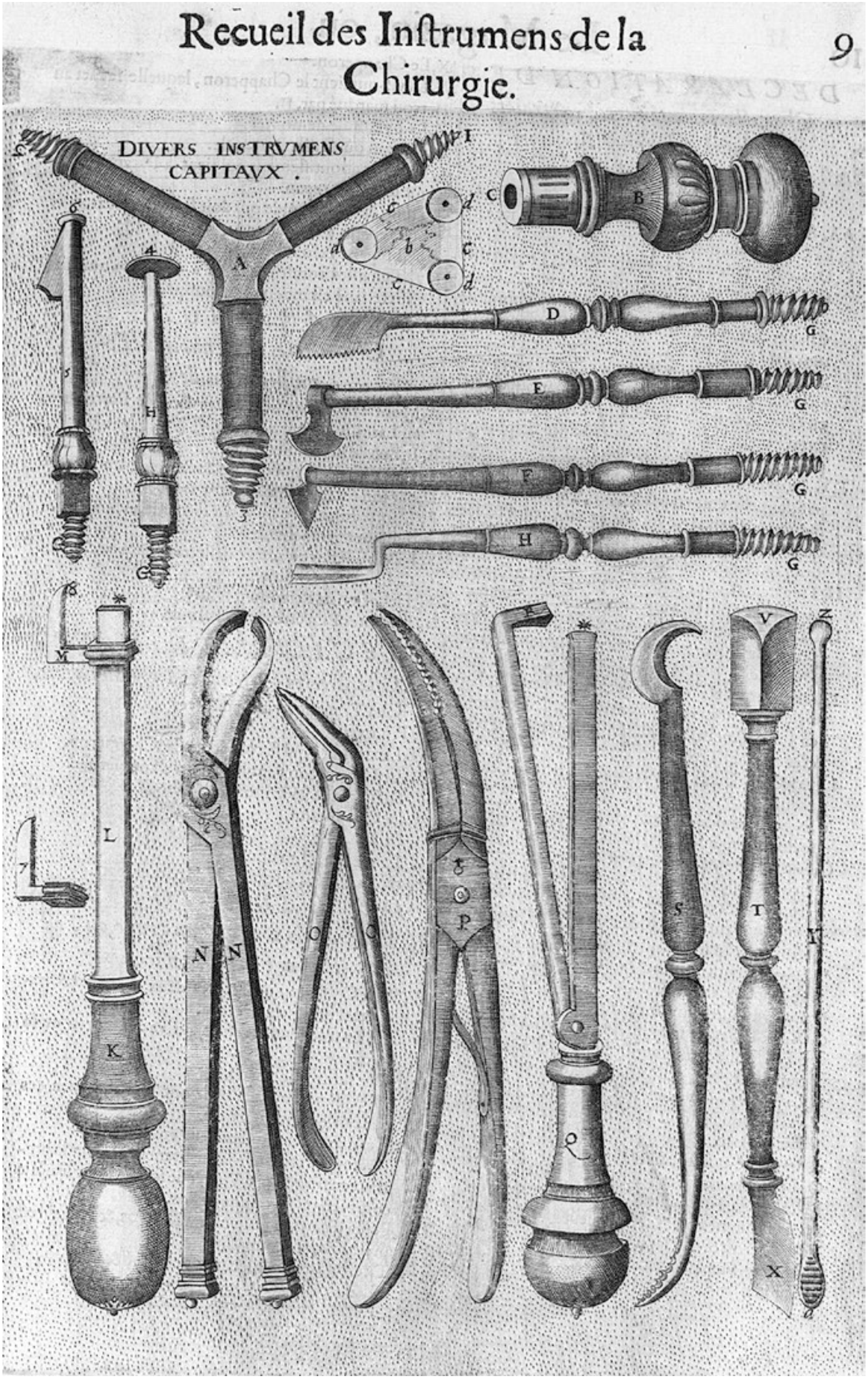


Fig. 13.2 (continued)

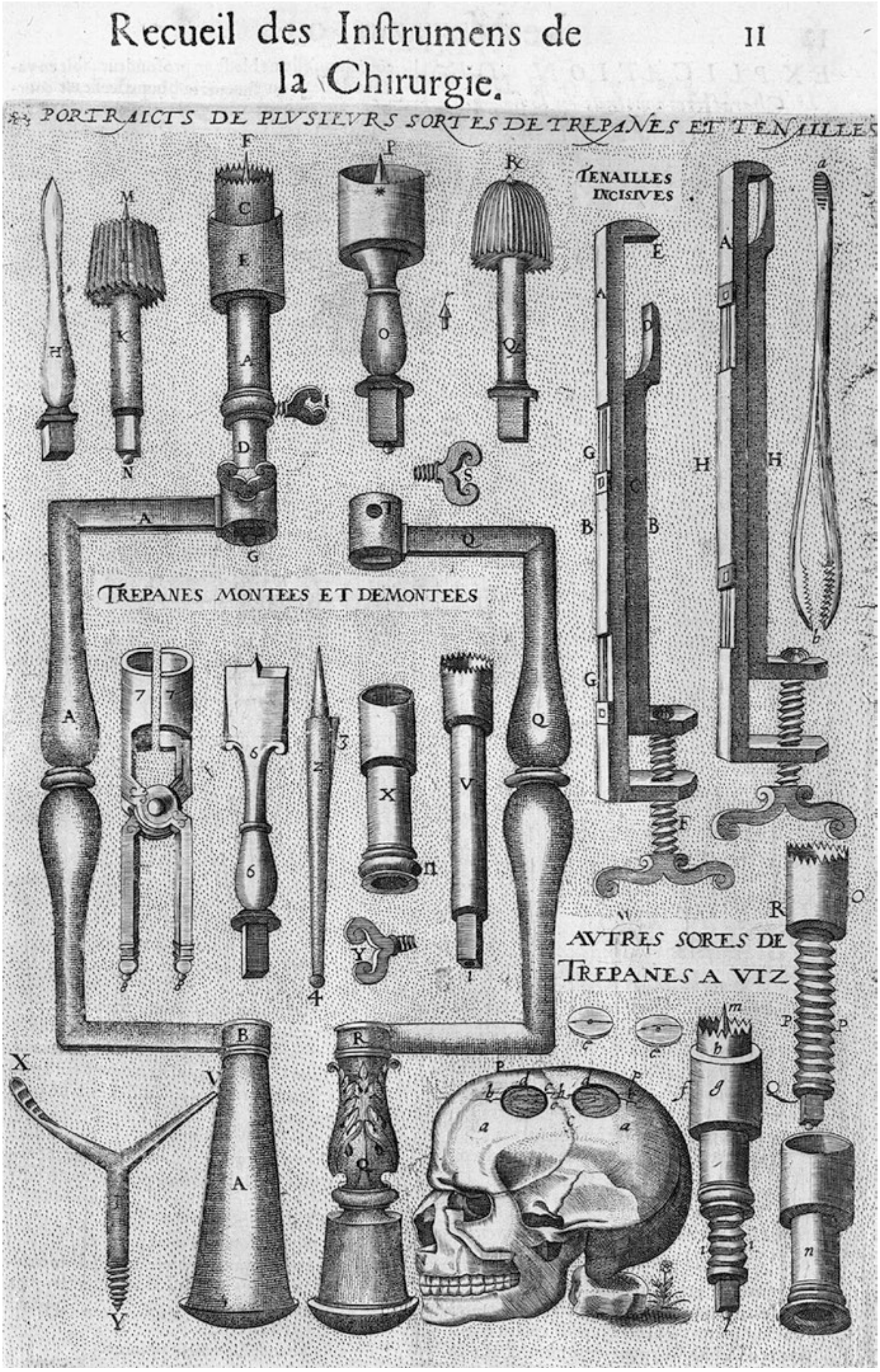


Fig. 13.2 (continued)

– A: shows a *'tirefond'* of 3 ft. of different size and used to raise fragments and that can also be used for trepanning.
– B: handle (*'L. Manubriolum'*) of the small important instruments, where the instrument is placed in an orifice to the effect (C).
– D: small saw (*'L. serrula'*) to cut the skull bone.
– E, F, H: shows several *'rugines'* or *'gouges'* (*'L. radulae, scalpa rasoria'*) with a round or sharp tip, which the ancients used to trepan but which now only serve to discover if the fracture penetrates the two cranial tables.
– H: is the depressor of the *'membrane'* (dura mater) that is used after trepanning to depress the dura to know if there is something between it and the bone. It should not be confused with the *'meningophylax'* of the ancients. One end is marked with the number 4 and the other end that gets into the hole of the handle B is marked with the letter G.
– 5: the lenticular (*'L. scalper lenticularis'*), which resembles a penknife and in which its end instead of being pointed has a round and flat lentil (6) in order not to injure the dura mater.
– G: the end of all instruments that goes into the hole C in handle B is marked with the letter G.
– K: a very comfortable type of lift, with a square shank (L) and its closed end (∗) that rests on the bone, and a sliding hook (M, N) whose tip (8) goes under the bone.
– N: incision pincers to cut some bone chips.
– Or: Bec de Lezard to pull some bone splinters.
– P: Bec de Corbeau.
– Q: another elevator (*'L. elevatorium bifidum'*) pointing to the end (∗) that should be placed under the healthy bone and the end (R) that should be placed in a notch of the bone to elevate it.
– S: another elevator with a serrated end and the other with semilunar ending.
– T: sharp instrument used to cut the *'muscular and pericranium leather'* layers of the head (scalp and muscles). It has one side cut (X) and the other thicker but also cutting to separate the parts more attached to the skull (V).
– Y: probe suitable for probing if there is a fracture of the skull, with one side rounded and of medium thickness (Z) and another similar to an elevator (a).
– b: shows how to achieve a large cranial opening by making three separate holes (d) and join with a saw. He says that others directly make the linear sections of the bone (c) directly with the saw, which is longer and more painful.

In the second plate, on page 11, Guillemeau shows the trepans and other instruments for trepanation, grouped in three areas:

– *'Trepanes montees et demontees'*: the whole and mounted trepan is shown (A), where the different parts of the trepan are marked with letters. Guillemeau highlights what he says is the proper trepan (CD) (Greek: *'trepanon chynicida'*; Latin: *'terebellum, trepanú stritatum, sera teres'*; Celso: *'modiolu's*; French: *'sies rondes dentelees, trepan dentelé'*), with the hood (E) (Greek: *'abaptiston'*; Latin: *'trepanum securitatis'*; French: *chaperon*), and the pin (F, G) (*'pyramide'*) that protrudes a little and that serves to fix the position of the trepan while it is used. Several letters and numbers indicate the different components of the disassembled trepan (O, P, Q, R, S). Around the assembled and disassembled trepans there are a sort of different attachments for perforation. Perforating lancet marks the point where the pyramid will be applied later (H). Another type of trepan is larger in the base than in the end (K) (Latin: *'Terebelum alarum'*; French: *'Trépan crenellé'*). This is a trepan that cannot sink. The slits or wings cut delicately (M) and the pyramid goes from part to part (M, N). A third type of trepan cuts only meat (O), so that its cutting edge (∗) is very sharp, like a knife, and should not be sawn. It serves to cut the soft tissues of the pericranium once cauterised. It has a pyramid going from part to part (P). Another type of trepan is to cut the bone in the shape of a thimble (Q), with a very sharp grooved surface below and at the sides. It also has its pyramid (R). A true trepan

without hood or pyramid (V), a protective hood (X), a pin (3, 4) and an exfoliating trephine (6) are also depicted.
- *'Autres sortes de trepan a viz'*: a screw trephine is also described, which draws mounted (f) and disassembled (or, R), with the following fundamental elements: P, screw; M, hood; h, trepan; l, m, pyramid.
- *'Tenailles incisives'*: pincers named Bec de Perroquer are shown opened (B, B) and closed (H, H), together with a small clamp and elevator (a, b).
- Finally, a skull is also drawn in the plate, where the left frontal and parietal bones (a, a) and a fracture (b, b, b) crossing the coronal suture are pointed (c, c, c), along with two trepans (d, d), and the two raised bone discs (e, e). There are also two instruments related with the elevation of the bone disc obtained after trepanation, a round clamp (7) which is suitable for grasping the bone disc once it has been trepanned and the *'tirefond'* of 3 ft. or branches (T), with one end that can cut the bone (V), another that is a small elevator (X) to lift the bone disc and see if it is loose and the third (Y) with screw to finally lift the bone.

13.2 Italian Surgeons: de Vigo, Berengario, della Croce, Bottallo and d'Acquapendente

A great number of surgeons showed interest in cranial trauma, surgery and trepanation in Italy. We are now to discuss their contributions to the cranial surgery and, particularly, to the development of surgical instruments for trepanation. The authors are arranged following the date of publication of their books.

A good example was Giovanni de Vigo (1450–1525), an Italian physician and military surgeon, who published in Latin *'Practica in arte chirurgica copiosa'* in 1516 and *'Practica compendiosa'* in 1517. We have consulted the translation from Latin into Spanish that carried out Miguel Juan Pascual in 1717 [3]. There are references about skull fractures in Chap. IV of volume III. We would like to comment briefly that the first chapter of volume V, which is written as a prologue, speaks about 'Healing the unconfirmed French disease' (syphilis). This topic was included in other medical and surgical texts of that time. The author initially described comminuted fractures related to wounds. However, he soon focused on special fractures: skull fracture without wound, depressed skull in children without wound, isolated fracture of the outer or internal table and skip fractures that are distant from the point of impact. He then described the symptoms of a fracture. Some symptoms appear immediately or during the first day, such as vomiting, seeing flashing lights in front of the eyes, vertigo, vision loss or falling to the ground after the impact. All of these symptoms are clear signs of fracture or bleeding through the dura mater. If there is brain damage, the symptoms are apoplexy, scotoma, vertigo, limb stupor followed by fever and stiffness. If the wound is large, brain matter can come out of it. He also focused on those cases where there was no fracture. If there is no fracture and blood is pouring under the bone and it decays, the patient shows an intense pain and inflammation. These symptoms are almost lethal in all cases. The severity and the onset of these symptoms depend on the amount of blood that leaks out. If it is significant they appear within 7 days in summer months and within 10 days in winter. He later reviews the diagnostic methods of the fracture. They varied considering the mechanical circumstances of the trauma; opening the pericranium if there was no wound or opening or enlarging the wound to examine it with the finger or applying writing ink to search for unnoticeable fractures. The fracture could be treated in two ways, by cutting, removing or lifting the bone or, alternatively, by desiccation and tissue growth. However, he did not speak about trepanation. He described in a detailed way all pastes, ointments and treatments to be applied in each case, including the strict recommendations about feeding the patient.

However, we must highlight de Vigo's nine rules that every physician must take into account before the cranial surgery: (1) the severity of the prognosis must be evidenced before the attendants and the patient's relatives so that they do not blame the physician for his or her death if things go wrong; (2) the intervention must not be carried out by someone who has a weak spirit; (3) cranial sutures must be cared to prevent the dura mater from falling onto the brain as the dura mater is fixed to the sutures; (4) physicians must avoid operating during the full moon as the size of the brain increases then; (5) remove and dilate the bone, particularly in the declining areas to make it easier to empty the material; (6) determine the amount of bone to be removed: it must be done only in the lower areas for long longitudinal fractures, whereas it must be removed in full if it is depressed; (7) if it is difficult to remove the bone pink oil can make it easier; (8) the intervention must be carried out as carefully as possible, without compressing or injuring the tissues; and (9) physicians must try to carry out the intervention before 7 days in the summer and before 10 days in winter, although the sooner the better.

He later referred to those patients with fracture symptoms but who had no wound or pericranium contusion or with no skull fracture or contusion. He attributed this to the rupture of a vein in the brain, which causes the same symptoms without a wound or fracture. Regardless of the intensity of the symptoms, there were no indications of surgical treatment for these cases and the author described detailed medical treatments. Finally, he described the head depressions in children and adults, which were treated in a traditional way.

This careful attitude towards trepanation changed in his second book *'Practica compendiosa'*, where de Vigo recommended trepanning fractures to drain blood effusions that compressed the brain. He described then his set of instruments for trepanning, made of three elements. The first one is the trephine crown with a central pin (*'instrumentum masculinum'*) to start the trepanation. The second one was a crown without central pin to continue with the drilling (*'nespula femina'*). Finally, a screw that was slightly introduced in the hole made with the pin to drill the internal table (*'instrumentum securitas'*) somewhat breaks it and removes it partially. This allowed to introduce then the *'lenticular'* to end the trepanation without injuring the dura mater.

Jacopo Berengario (1457–1530) was an Italian physician who was trained in Bologna, and wrote the book *'Tractatus de Fractura Calvae sive Cranei'*. The book was published in Bologna in 1518 in Latin, with a second edition before 1535. Other subsequent editions were published in Venice in 1535 and Leiden in 1629, with three reprints in 1651, 1715 and 1729. He wrote the book due to his concern about the treatment that Lorenzo II, Duke of Urbino, underwent in 1516 when he was injured in the head with a harquebus. He was trepanned and Berengario was present during the intervention, witnessing how the instrument dipped inside the duke's skull. Fortunately, this had no negative consequences [4]. The book was published only 2 years after the Duke's trepanation aimed by this dramatic event.

We have reviewed the translation into English of the edition of 1651 of this book [5], which was carried out by L.R. Lind in 1990 [6]. Curiously the book only includes illustrations concerning the trepanation. This has been understood as an evidence of Berengario's interest on this issue or maybe a consequence due to the lack of time or money when launching the edition, as completing the work with all illustrations would have meant a delay. Berengario divides his instruments into trepanning devices or perforating tools which include raspatories, scalpels, forceps, small saws and lenticular of Galen; elevators; and, finally, extractors, such as the serpentine. Berengario recognises that some instruments had to be invented for special purposes by the physicians and had himself invented some which he used only once. As we have said above, Berengario described and illustrated the *'vertibulum'*.

The illustrations in the successive editions of the book *'De fractura crani'* by Berengario are an example of how the illustrations of the instruments are changing in the re-editions and reprints. Curiously, these figures are perhaps the most reprinted figures about trepanation instruments in modern times. In this late edition published in 1651 [5, 6], the instruments are better drawn than in the first one of 1518 and in the edition of 1535, and the names of the instruments are no longer appearing on the side. There are also some differences in the description of them. The instruments and the descriptions that we find in the book are the following:

- Page 281: Berengario says that 'the first instrument that is represented I call it *"vertibulum"* or *'verticulum'* because when it is rotated it perforates the bone, according to the shape of the instrument that is attached. It has a hole in the lower part that serves for all those small instruments called *'terebra'*. You start by placing the smallest and then using the wider one. This instrument was called at the beginning *'receptaculum'*, because it received all the necessary instruments for trepanation. Berengario now describes the handle and its parts. There is another instrument called *'terebrum'* that also fits the hole of the receptacle previously described.
- Pages 282 and 283: Berengario says that as you can see, this instrument is hollow (*'canulatum'*), has a round shape and its end is made of iron to pierce the bone. In the middle it has a sting, ending in a pointed end with three or four sides that comes out a bit from the end and that erodes the bone. This instrument is appropriately called *'tererebrum'*. By means of this sting the instrument is fixed to the bone easily and can also be easily removed to avoid injuring the brain. Experts remove it when half of the skull has been pierced and then continue drilling with the instrument called *'fimile'* (female). The sharp instrument is called *'masculus'* (masculine). In addition, the instrument has the shape of a horse's hoof. This arrangement prevents the instrument from sinking into the brain, since only the narrow part penetrates and the wide part is left outside. Other similar instruments have been described by Bononienfes, as Guido de Cauliaco (Guido de Chauliac) says. However, in my right mind, this instrument improves any other, used by expert and knowledgeable doctors.
- Page 284: Eight instruments called *'terebra'* are presented, all of them to be placed in the same receptacle and the first to be used.
- Page 285: Another instrument called *'trepanum'* is presented. It was called *'terebellum'* by Haly (Haly Abbas), it was named by Galen and it was called *'trepanum & perforarium non profundans'* by Avicenna and *'terebrum non profundans'* by Ab Albucasi (Albucassis). Curiously, the instrument, in the form of T, ends in a thread and not in an acuminate point.
- Page 287: A *'forceps incides'* and a *'tenalia'* or *'serpentine'* are represented.
- Page 289: It represents an *'elevator magnum'* and another elevator, which he calls *'rostrum accipitris'* (falcon's beak).
- Page 290: Several *'scalpra'* are represented.
- Page 292: A *'serra'* (saw), the *'scalprum rectum'* (chisel) and the *'malleo plumbeo'* (heavy hammer) are represented.
- Page 293: This instrument is a *'lenticulare'* or *'lentiticium'*, on which Galen made a real panegyric. It must be carefully hammered with the hammer so that it has the least effect on the patient's brain. At its tip there is a small expansion in the form of mustard lentils so as not to puncture the brain. It allows to cut the bone and the evacuation of the humours that irritate the brain. At its other end, it is inserted into the receptacle of a handle.

Most of the figures of tools for trepanations in modern papers and written media come from Giovanni Andrea della Croce (c1515–1575), a son of barber surgeon, who also became surgeon in Venice (Italy), the town where he was born, in 1532. He published the work *'Chirugiae Universalis Opus Absolutum'* in Latin almost at the end of his life. It has had many re-editions and it was later translated into Italian, English and German [7, 8]. The work is an example of the encyclopaedic knowledge of the Renaissance, as it endeavoured to gather all the information they had about a topic until that moment. For this reason, all known surgical instruments are gathered in this work, with drawings and instructions for use (Fig. 13.3). Some of them were interpreted by the author as he actually did not know them or had ever used them before. He carried out a systematic review and translation of the names and the symptoms of the diseases from

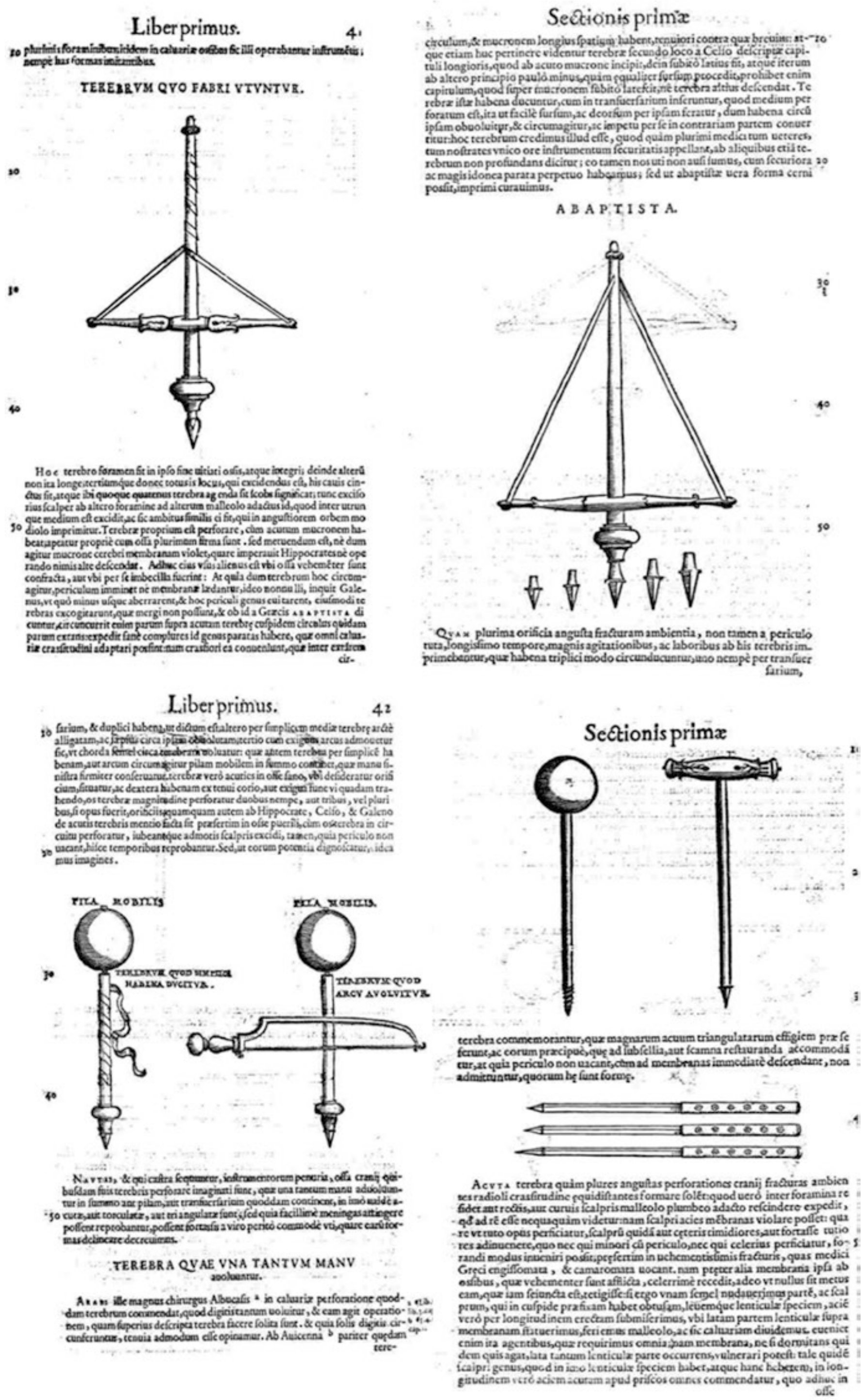


Fig. 13.3 Instruments related to the trepanation by Giovani Andrea della Croce (Della Croce, GA. Chirurgiae universalis opus absolutum. Venetiis: Iordanus Zilettum, 1596)

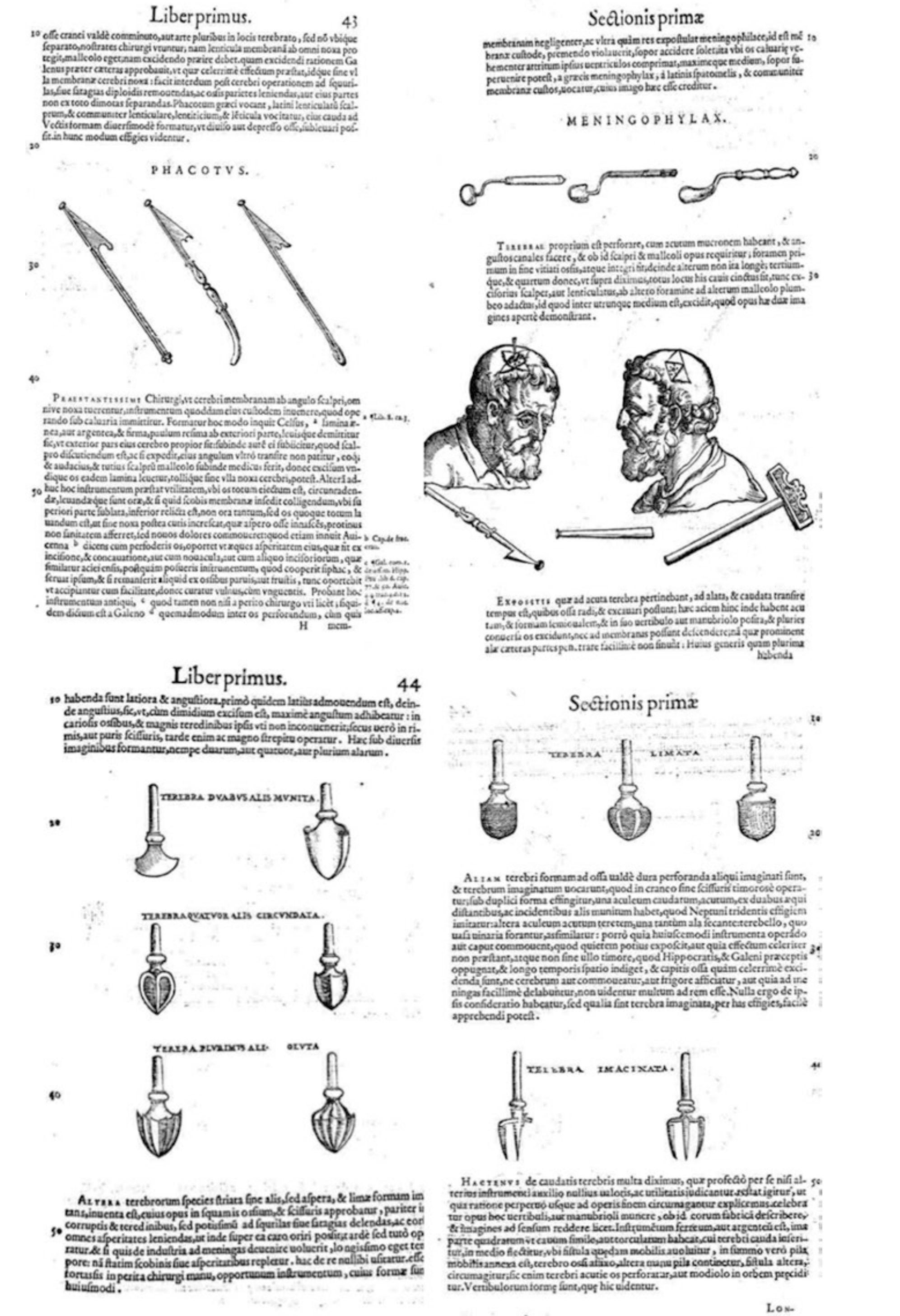
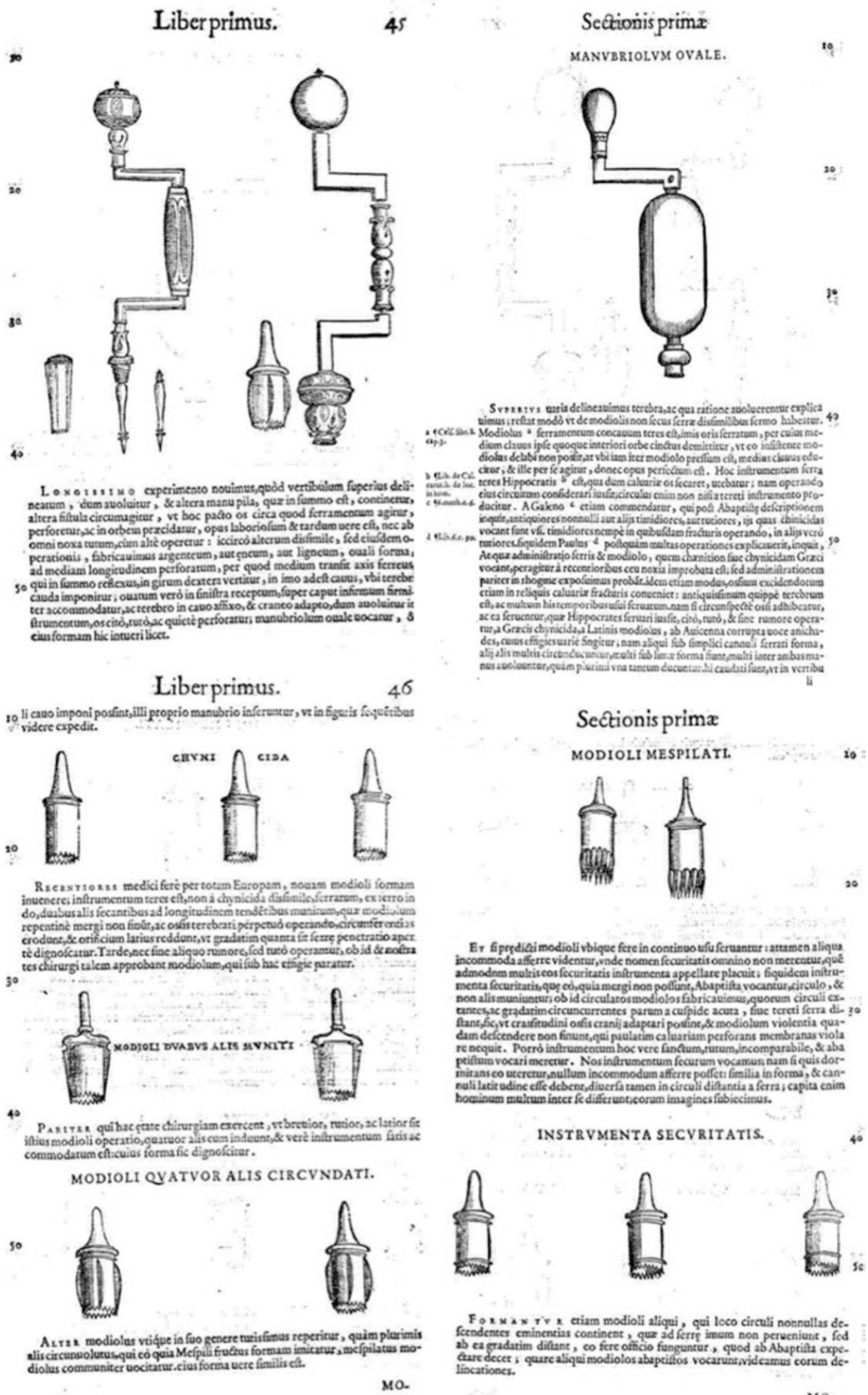


Fig. 13.3 (continued)



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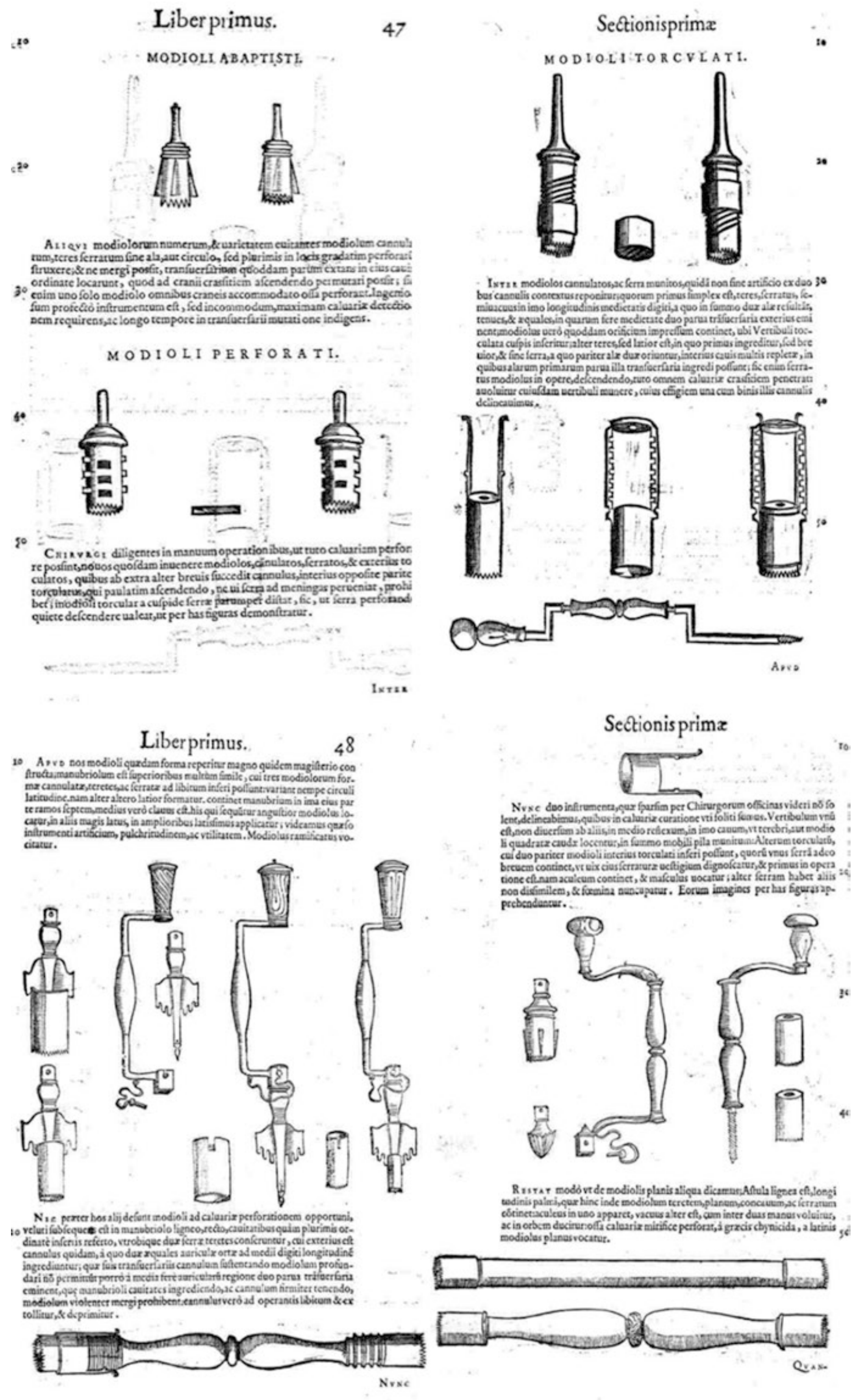

Liber primus. 47

MODIOLI ABAPTISTI.

ALIQVI modiolorum numerum,& uarietatem euitantes modiolum cannulatum, teres ferratum sine ala, aut circulo, sed plurimis in locis gradatim perforatum struxere; & ne mergi posit, transuersarium quoddam parum extans in eius cauis ordinate locarunt, quod ad cranii crassitiem ascendendo permutari posit; sic enim uno solo modiolo omnibus craneis accommodato ossa perforant. Ingeniosum profectò instrumentum est, sed incommodum, maximam caluariæ detectionem requirens, ac longo tempore in transuersarii mutati one indigens.

MODIOLI PERFORATI.

CHIRVRGI diligentes in manuum operationibus, ut tuto caluariam perforare posint, nouos quosdam inuenere modiolos, cānulatos, ferratos, & exterius torculatos, quibus ab extra alter breuis succedit cannulus, interius opposite pariter torculatus, qui paulatim ascendendo, ne ui serra ad meningas perueniat, prohibet; modioli torcular a cuspide serræ parumper distat, sic, ut serra perforando quiete descendere ualeat, ut per has figuras demonstratur.

INTER

Sectionis primæ

MODIOLI TORCVLATI.

INTER modiolos cannulatos, ac ferra munitos, quidā non sine artificio ex duobus cannulis contextus reponitur; quorum primus simplex est, teres, ferratus, semiuacuus in imo longitudinis medietatis digiti, a quo in summo duæ alæ resultāt, tenues, & æquales, in quarum fere medietate duo parua trāsuersaria exterius eminent; modiolus uerò quoddam orificium impressum continet, ubi Vertibuli torculata cuspis inferitur; alter teres, sed latior est, in quo primus ingreditur, sed breuior, & sine serra, a quo pariter alæ duæ oriuntur, interius cauis multis repletæ, in quibus alarum primarum parua illa transuersaria ingredi possunt; sic enim serratus modiolus in opere, descendendo, tuto omnem caluariæ crasiciem penetrat; auoluitur cuiusdam uertibuli munere, cuius effigiem una cum binis illis cannulis delineauimus.

APVD

Liber primus. 48

APVD nos modioli quædam forma reperitur magno quidem magisterio constructa; manubriolum est superioribus multùm simile, cui tres modiolorum formæ cannulatæ, teretes, ac ferratæ ad libitum inferi possunt: variant nempe circuli latitudine, nam alter altero latior formatur. continet manubrium in ima eius parte ramos septem, medius verò clauus est. his qui sequūtur angustior modiolus locatur, in aliis magis latus, in amplioribus latissimus applicatur; videamus quæso instrumenti artificium, pulchritudinem, ac vtilitatem. Modiolus ramificatus vocitatur.

NEC præter hos alij desunt modioli ad caluariæ perforationem opportuni, veluti subsequens est in manubriolo ligneo, recto, cauitatibus quàm plurimis ordinatè infernis referto, vtrobique duæ serræ teretes conseruntur, cui exterius est cannulus quidam, à quo duæ æquales auriculæ ortæ ad medii digiti longitudinē ingrediuntur; quæ suis transuersariis cannulum sustentando modiolum profundari nō permittūt porrò à media ferè auricularū regione duo parua trāsuersaria eminent, quę manubrioli cauitates ingrediendo, ac cannulum firmiter tenendo, modiolum violenter mergi prohibent; cannulus verò ad operantis libitum & extollitur, & deprimitur.

NVNC

Sectionis primæ

NVNC duo instrumenta, quæ sparsim per Chirurgorum officinas videri nō solent, delineabimus, quibus in caluariæ curatione vti soliti sumus. Vertibulum vnū est, non diuersum ab aliis, in medio reflexum, in imo cauum, vt terebri, aut modioli quadratæ caudæ locentur, in summo mobili pila munitum: Alterum torculatū, cui duo pariter modioli interius torculati inferi possunt, quorū vnus serrā adeo breuem continet, vt uix eius serraturæ uestigium dignoscatur, & primus in operatione est. nam aculeum continet, & masculus uocatur; alter serram habet aliis non dissimilem, & fœmina nuncupatur. Eorum imagines per has figuras apprehenduntur.

RESTAT modò vt de modiolis planis aliqua dicamus; Astula lignea est, longitudinis palmi, quæ hinc inde modiolum teretem, planum, concauum, ac serratum cōtinet: aculeus in uno apparet, vacuus alter est, cum inter duas manus voluitur, ac in orbem ducitur: ossa caluariæ mirifice perforat, à græcis chynicida, a latinis modiolus planus vocatur.

QVAN-

Fig. 13.3 (continued)

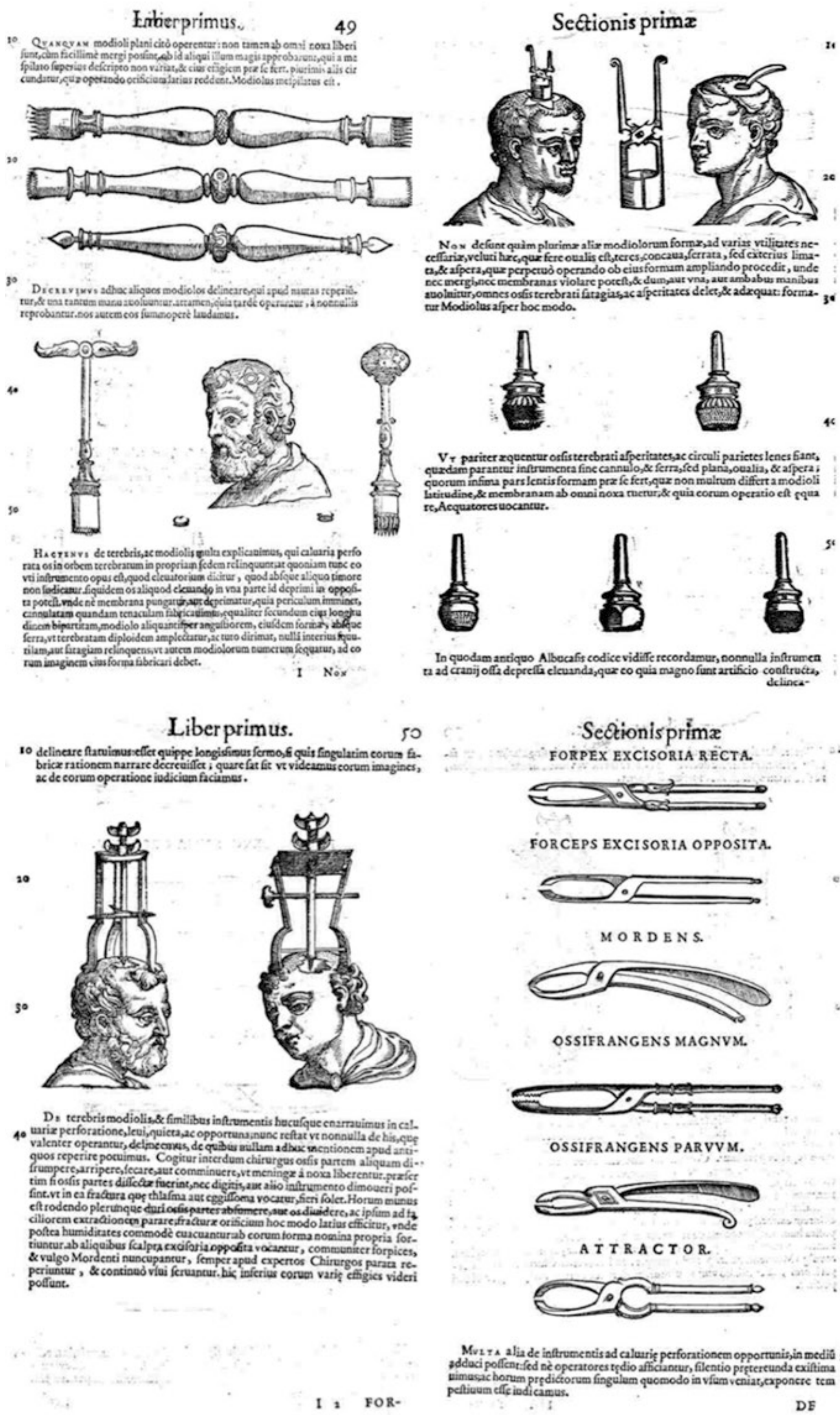

Fig. 13.3 (continued)

Greek, Latin and Arabic languages. At the end of the work, in the seventh volume and over 71 pages he gathered a huge amount of illustrations of surgical instruments of all kinds (ancient, new) and among them we must highlight the drawings of the instruments used for trepanations, their description and their use.

Chapter X of the book deals on unnoticed narrow skull fractures, and includes the different instruments that might be necessary for examining and treating these lesions, such as knives, scissors, probes, shanks, bolsters, chisels, dissectors and different scrappers with the handles onto which they could be coupled, along with a mallet and a great amount of straight and short curved saws. Chapter XI focuses on those cases in which the membranes can be observed through the skull fracture and how to operate with iron instruments. It shows the different shapes of the incision on the pericranium. There are three different types: cross-shaped or tetragonal incision, triangular or right-angled incision and linear or straight incision. This chapter includes as a single instrument the shaver or razor blade. Chapter XII expressly refers to trepanning instruments (*'De terebris, modiolis, phacotis, scalpris, cycliscis, meningophilacis, ac aliis instrumentis ad cranii perforationes opportunis'*), which are drawn and described in detail.

The precise description of all these necessary instruments for trepanation is shown below following the number of the pages of the original (Fig. 13.3):

– *'Terebra'* of arch: The first three figures in pages 41, 41 reverse and 42 represent the *'terebra'* that work with the three mechanisms of acceleration with strings. The piercing tip is pointed in all of them and different sizes are presented. The perforators are equipped with a safety flange to prevent them from sinking (*'terebrum non profundns dicitur'* or *'abaptista'*).
– Handled *'terebra'*: Some perforators that can be used with one hand are drawn in the page 42 reverse, mounted on a straight stem or ending in a ball or T grip for handling. They have very thin and pointed drills, one of them finished in a spiral thread.
– *'Phacotus'*: On page 43 three different models of an instrument equivalent to the lenticular knife are drawn, although it is not called by this name, which is the one that will receive later.
– *'Meningophilax'*: Three different models are drawn and in a lower drawing the way to use them, next to the lenticular or dura mater depressor. Below the *'meningophilax'* there are two figures of patient heads where the use of the *'terebrae'* is demonstrated. Della Croce says that this piercing instrument is used to make holes, the first far from the injury and then many others around it. The holes allow to obtain a piece of bone directly or after joining them with chisel and hammer or with the lenticular knife.
– Punches and drills: Many types of *'terebra'* are drawn according to the shape of the tip: with two wings, with four wings, many wings, filed (*'limata'*) and in the shape of a trident (*'imacinata'*), which are different from the pointed ones.
– *'Vertibulum'*: Della Croce draws two regular braces (page 45), the first to mount the *'terebra'*, the second to mount the *'modiolus'* and a third one, with the thickened handle (*'manubriolum ovale'*).
– - *'Modioli'*: Different models of *'modioli'* are drawn in pages 46 and 47, some flatted, and others with two and four wings and long saw teeth, one of them short and the other long. Then there is a series of them with different security systems to control the depth of cutting, some with a safety flange located at different heights and the so-called unsinkable (*'modioli abaptisti'*), equipped with wings that act as stops. There is also a model with multiple perforations, to place a bar through the holes that would act as a stop system (*'perforati'*). Finally, there is a model with a second crown screwed on the serrated cutting crown, which allows fine selection of the depth of cut (*'torculari'*). All these *'modioli'* are hollow or cannulated and have at their base a proximal stem that allows their insertion and fixation at the distal end of the brace.
– On the back of page 47, Della Croce represents a complex instrument with two pieces. The first

piece is a *'modiolus'* that has two characteristics. The first one is that its base lacks a proximal stem and, instead, there is a hole where the distal end of the brace will be screwed. The second one is that the base has two extensions with hooks on its end. The second piece is also hollow, and the proximal part with grooves in its interior and a smooth distal part. When the *'modiolus'* is inserted into the brace, the second piece is passed out and left fixed at the desired height by hooking the hooks into the slots, whereby the depth of cut is selected.

– *'Modiolus ramificatus'*: On page 48, a curious system is drawn that allows inserting *'modioli'* of different diameter at the end of the brace.
– Double-straight handles (*'canulus'*) with different types of drills on either side and equipped with some of the security systems (pages 48 back and 49).
– Then come a series of figures that illustrate the way to make the perforation with *'modioli'*, mounted on T-handle or ending in ball, extracting a disc of bone, which is drawn separately. On page 49, the way to extract the bone disc from the skull obtained after perforation is illustrated. Three instruments particularly designed for this purpose are depicted. The first has the shape of a pincer (*'cannulata tenacula'*), the second is an elevator and the third is a gadget with non-cannulated piercing crowns.
– On page 50 is the last of the illustrations of the trepanation with the representation of the system of elevation of fragments of three legs and two legs, torcula's type.
– Bone forceps: A total of six different types of bone forceps are collected, for excision, breaking, fragmenting or pulling the bone.

Moreover, the trepanation chapter ends with the description of six illustrative clinical cases. They include some particularly interesting illustrations in two of the cases that represent the general atmosphere of the trepanation. Surgery was carried out at the patient's bedroom. The patient was lying face down and the surgeon and his assistants were placed around him. The patient's relatives warmed the room. All the windows were closed and there were animals running around the room.

Leonardo Bottallo (c1530–c1587) was an Italian physician, surgeon and anatomist who developed his professional activity throughout Europe. He gained a lot of experience in war surgery, particularly in wounds caused by firearms. He published his work *'De curandis vulneribus sclopettorum'* in Lyon in 1560, although it has had many subsequent re-editions. He focused on head wounds in Chap. XVI, titled *'De curatione vulneris capitis'* [9]. The text literally reproduces large fragments from the works of Hippocrates, Celsus, Galen, Vigo and others, but includes a set of very interesting figures (Fig. 13.4). In page 43 there is a figure with several perforator types *'terebra'* and *'modiolus'*, some equipped with *'abaptista'* systems and braces. The perforators are interchangeable and are attached to the handle with a pin. In page 46 are represented different types of *'scalpra'* and *'elevatoria'*.

We would like to highlight the enlarged cranial opening designs that are shown in pages 44 and 45 of the book. Large openings with different designs are done with repeated drills made with the *'terebra'* (*'terebratione reiterata'*). They were grouped when it was necessary. Separate drills could also be made. In this case the remaining bone between holes was resected with a *'lenticular'* or with the chisel and the mallet. The book illustrates four drills grouped in a line and other four groups forming a square. Another drawing shows two, three and four separate drills. The bone to be resected between them is marked. The third way to achieve large windows is even more interesting. A groove is marked on the skull with a *'scalpra'* and then a saw (*'serra'*) is used to directly cut the whole thickness of the bone. Botallo shows in his book two cranial resections of this kind: a rectangular resection and a triangular one. A commented compilation of all Botallo's works was published in 1660 under the title *'Opera omnia medica & chirurgica'* [10]. It described the instruments required for a cranial trepanation, including the *'terebra'*, *'modiolus simpli'* and *'modiolus abaptista'*, *'serri'*, *'abaptista terebra'*, *'scalpri'*, *'lenticular'*, *'forceps'*

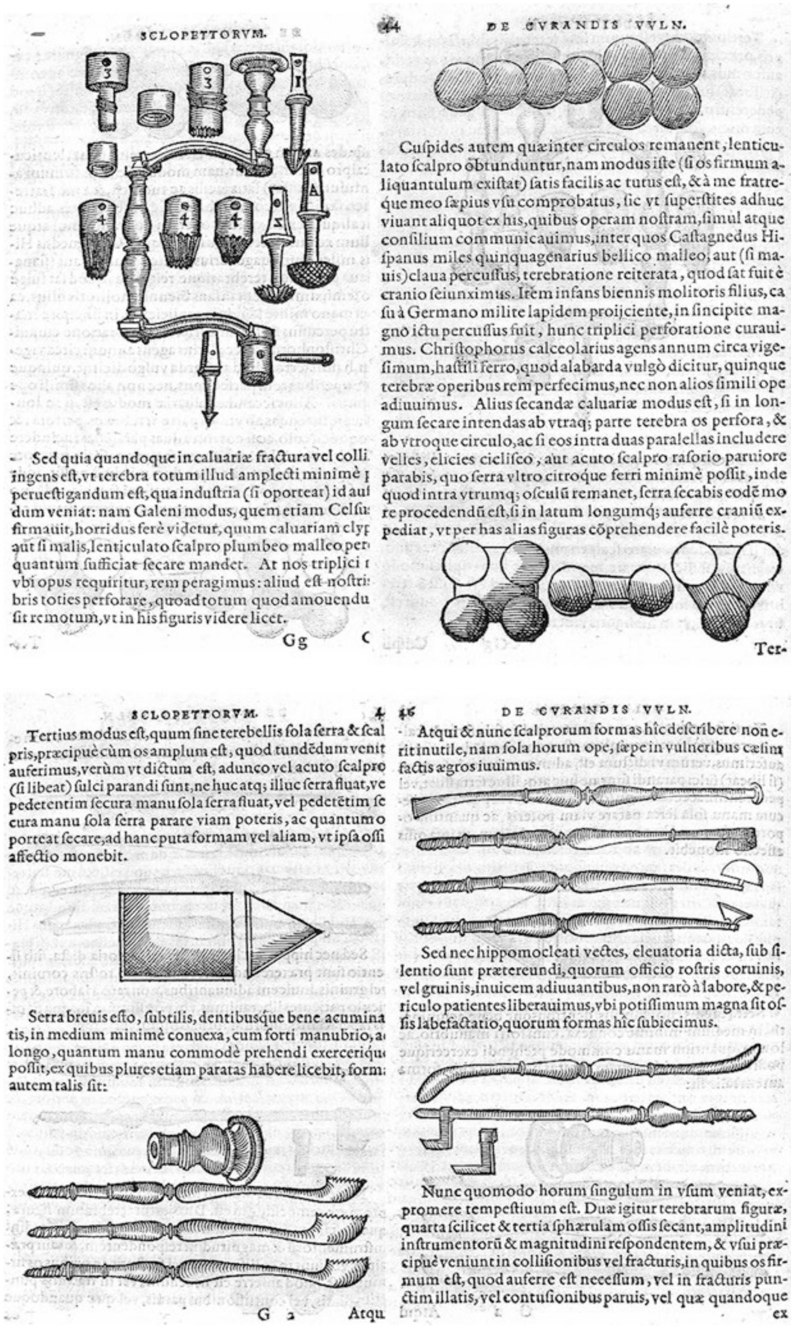

Fig. 13.4 Instruments related to the trepanation by Leonardo Bottallo (Bottallo, L. De curandis vulneribus sclopettorum. Francofurti ad Moenum: Georgium Corvinus, 1575)

and *'elevatoria'*. He described his own instrument as a *'modiolus Botalli'* and the suitable procedures for each type of lesion.

Finally, another Italian surgeon was Girolamo Fabricius d'Acquapendente (1537–1619). He was also an eminent anatomist at the University of Padua, where he inherited the Chair for Surgery from Gabriele Fallopio. He lectured, in turn, William Harvey. His most relevant work in the field of surgery was *'Opéra chirurgica'*, which was initially published in Latin in 1617. However, many later editions were published in several languages [11–14]. We have consulted the French edition from 1643 which, contrary to the original one, is divided into two parts. The second book of the first part, which corresponds to the original work, includes some chapters about head wounds. Chapter XIII addresses the really important anatomical considerations of the head areas for a good knowledge of such wounds. He described the pericranium, the skull along with its sutures, the dura mater, the pia mater and finally the brain, located under the pia mater, along with its ventricles. Chapter XIV is about head wounds and Chap. XV about the symptoms and signs of head wounds. It covers all types of trauma, including wounds, fractures and dura mater and brain injuries. He pointed out that 'all head wounds are dangerous'. He systematically described the treatment in the next chapters. He distinguished different types of treatments: those for simple and external wounds (Chap. XVI), those for skull fractures that do not reach the dura mater (Chap. XVII), those for penetrating skull fractures that do not injure the dura mater (Chap. XVIII), those for dura mater injuries (Chap. XIX) and those for pia mater and brain injuries (Chap. XX). Finally, the book also covers frontal fractures (Chap. XXI) and fractures of the eyebrows (Chap. XXII).

As we will see, d'Acquapendente was very aggressive concerning the indications of trepanation and cranial surgery. Those fractures that did not reach the dura mater were exposed by making a cross-shaped incision. They were scrapped with a *'racle & rugine'* after denuding the skull until they completely disappeared. He showed his opposition to Celsus' traditional conservative treatment ideas with strong arguments. He used two types of *'rugines'*. The first ones, which were similar to the ones used for cutting wood, with a triangular, square or round shape, incised and cut the bone. The second ones were used to scrap the bone. If the physician was uncertain about the fracture, normal black ink could be poured to confirm it, as it was less aggressive than vitriol.

Those fractures reaching the dura mater could be simple or depressed. The treatment of the injuries aimed to avoid accumulations that could compress the dura mater or prevent the bone fragments from eroding it. According to the author, both cases were very dangerous. For this reason, he recommended cutting the skin and the bone after criticising again the traditional treatment. He used the strongest *'rugines'* for the bone, the *'tariere'* (borehole), which was similar to the one used by carpenters, allowed to drill the outer table. Finally, he used the *'trepan',* which was 'round, hollow, had short teeth and a stopcock or braking system at the middle section'. Despite its name, the description of the instrument seems to match a trephine. He reminded the need of using rose oil or milk as lubricants and cooling the trepan with water. He then highlighted the dangers of dipping the trepan inside the skull as it involved the risk of fatally injuring the patient. He offered some recommendations with regard to this topic. However, the solution he suggested was an instrument that he had invented himself and that had *'d'un trepan & d'une tariere, & auquel ie donne des ailes qui empeschent qu'il ne tombe sur la dite dure mere'* ('Of a trepan & drill, & to which I give wings which prevent me from falling on the said dura mater'). The margins of the trepanation were harmonised with a *'lenticulaire'* to avoid eroding the dura mater with any bone spicule. He then described the most suitable treatments.

If the dura mater had been injured he considered absolutely necessary to remove everything that accumulated over it. To do so, it was necessary to open the skull if the opening caused by the fracture was not enough. On the contrary, if the pia mater and the brain had been injured, there was a risk they could decay as they were exposed to air. For this reason, the treatment only consisted of washing and cleaning the wound as the skull should not be opened.

D'Acquapendente also described the instruments he used for cranial surgery that are drawn in a different way in the successive editions of the book, many years after he passed away. The edition in French of 1643 has no illustrations, and the one of 1658 has three plates with illustrations of cautery, saws and a trepan with handle in T. The draws have written the name of the instrument illustrated. On page 508 three instruments are shown for coronal suture cautery, on page 519 three bone saws are given and, finally, on page 515 the trepan with the T-handle and the male drill crown (*'masle'*) and feminine (*'femelle'*) is represented. It should be noted that the central tip that characterises the male trepan has not been drawn (printing mistake?) (Fig. 13.5).

The Latin edition of 1666 has several plates at the beginning of the book gathering surgical instruments, not only for trepanation, but also for other surgical interventions. The name of the instrument is written near each instrument. Plate B depicts three instruments for cautery of the

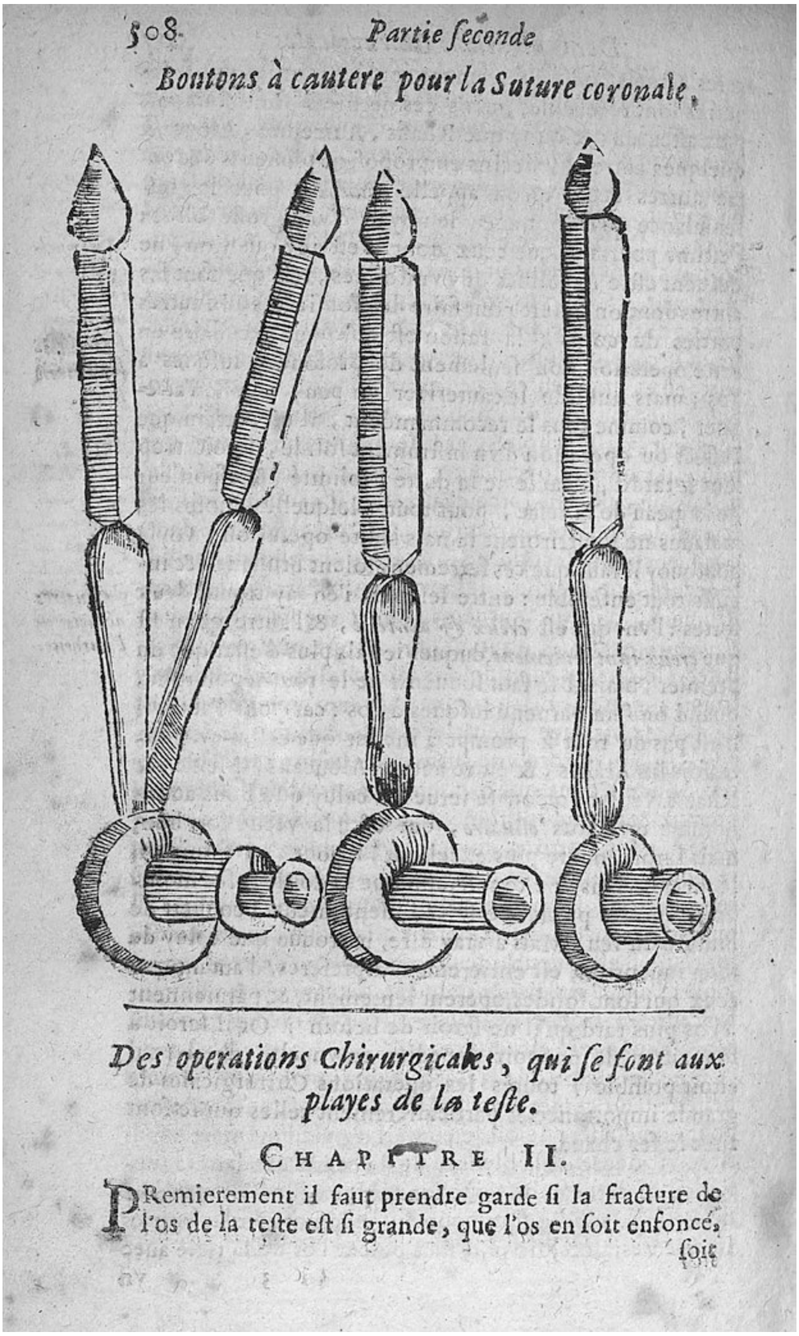

Fig. 13.5 Instruments related to the trepanation by Girolano Fabricius d'Acquapendente (D'Acquapendente, H. Oeuvres chirurgicales divisées en deux parties. Derniere edition soigneusement reveue & enrichie de diverses figures inventées par l'autheur. Paris: Jean Pocquet; 1658)

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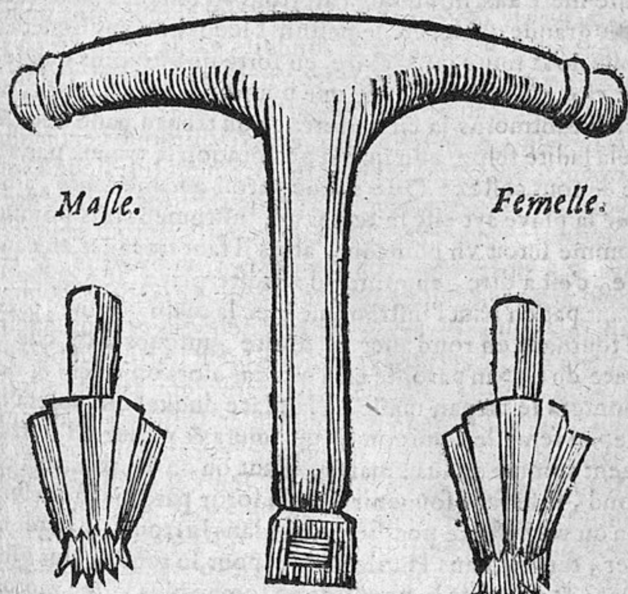
dit *modiolus* ayant quatre aiſles ; la ſuperieure qui tourne, eſt le manche de la tariere. Or cét inſtrument n'eſt ny trop peſant, pour ſe plonger ; ny trop leger, pour retarder l'effet de l'operation : outre ce, il n'eſt point trop grand, ne mene aucun bruit en operant, & la main du Chirurgien le conduit & gouuerne touſiours , ſelon que beſoin eſt, ſans qu'il faſſe aucune compreſſion conſiderable par ſa peſanteur : c'eſt pourquoy il opere promptement, auec ſeurté, & aggreablement, c'eſt à dire, ſans faire ny bruit , ny peur, & le plus ſouuent auec heureux ſuccez.

Trepan.



Apres auoir parlé des Trepans & de leurs differences, il faut que nous expliquions le *moyen* de ſe ſeruir de cét inſtrument , qui eſt cette operation chirurgicale , qui enſeigne comment il faut percer le crane auec le trepan. Sur quoy

Comment il ſe faut ſeruir dudit trepã.

Fig. 13.5 (continued)

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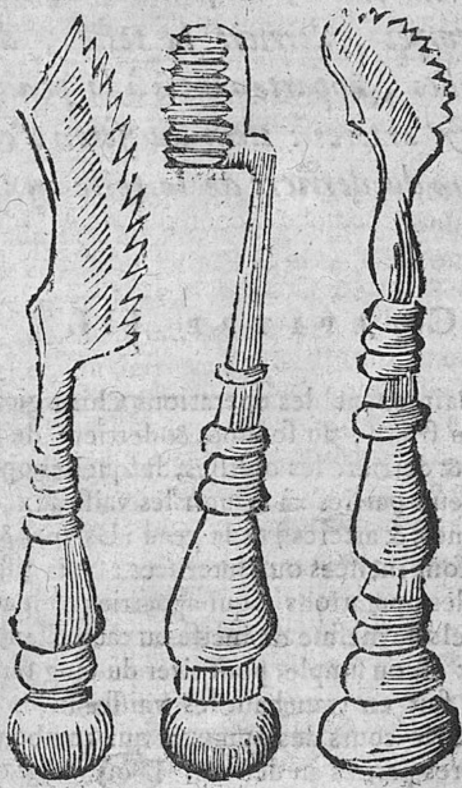
lors que la ſituation de l'os ou carié ou rompu, eſt telle, que pour l'oſter, il eſt beaucoup plus commode de ſe ſeruir de ces petites ſçies, que de tout autre inſtrument; voilà pourquoy i'en ay fait faire cinq de diuerſe forme & grandeur; deſtinées à cet vſage.

Diuerſes ſortes de Sçies.



La *ſixieſme* & derniere operation, eſt celle qui ſe pratique lors qu'il eſt queſtion d'enleuer quelque piece ou eſquille d'os, totalement ſeparée des autres, & qui neantmoins eſt entrefichée entre iceux; car alors on eſt cõtraint de ſe ſeruir de *tenailles dentellées*, pour l'emporter partie en la rompant, & partie en la coupant: Or ces tenailles ſont differentes, premierement en leur grandeur; car

comme

Fig. 13.5 (continued)

coronal suture presented at the top of the page. Plate C shows several scalpel blades and above the handle with a lower opening where they are threaded, and also a corrugated sheet chisel, a heavy-head hammer, a triploid screw, a triploid elevator for the bones of the skull and several scrapers. In the lower part there are two chisels, one straight and one curved and, finally, a drilling head with four wings and the central spike. Plate D portrays two saws and the *'trypana'*, with the T-handle (*'manubrium'*) and the male (*'mas.'*) and female (*'foemina'*) drill crowns. Below there are instruments for eye surgery. The Spanish edition of the book of 1673, translated by Pedro González de Godoy, has not illustrations at all.

D'Acquapendente described the surgical interventions 'from head to toe' in the second part of the work, including the instruments required to carry them out. He classified the interventions into three different types: those that were *'petites, fáciles & grandement douces'*, those considered *'difficiles & perilleuses'* and those that were *'tres violentes & tres cruelles'*, among which he included interventions of the head. The 12 interventions of the head that he described in detail were the following: cauterisation of coronal suture, lifting depressed fractures, trepanation, fracture scrapping with a *'rugine'*, smoothing the margins of the cranial opening with the *'lenticulaire'*, treatment of the skull bone 'decay', how to cut the bone between two openings and to cut it with pincers or forceps, how to fold and place back to its original position the dura mater when it is lifted or swollen with a depressor, how to saw the bone, removal of bone pieces, incisions on the sinciput and finally how to incise and drain a tumour called *'hydrocephale'*.

We are not going to describe them all. We will just focus on the considerations he made about trepanation. He tried to lift depressed fractures first with a light lifter that the Italians called *'lieva'*. If it was not possible, a stronger lifter had to be used. The *'elevatoire triploide'* was used whenever it was necessary. It was called that way because it had three legs or bases that leaned on the head. However, if there was not enough space the only thing the surgeon could do was to break the bone. If the fracture is not depressed, there is no other alternative but to pierce the bone to drain or evacuate the accumulations under it. To do so, he recommended using two instruments. One was called *'tariere'* in French or *terebra'* in Latin. The other one was an instrument called *'trepan dentellé'* or *'modiolus'*. He pointed out that the first one was completely similar to a driller used by the carpenters. The second one is an iron, hollow, round instrument with teeth around it. It is called *'trepan masle'* when it has a sharp, pyramid-shaped iron piece in the middle. If it does not include this piece, it is called *'trepan femelle'*. He then explained in detail the risks of dipping the abovementioned trepans inside the skull and the existence of unsinkable instruments that Hippocrates called *'abaptista'*. He recommended in first place to completely remove all the *'tariere'* or *'terebra'* and the *'trepan dentellé'* or old *'modiolus'* because, according to the author, they did not have a cap that prevented them from dipping, contrary to the current ones. He made the same suggestion concerning any instrument that could erode the dura mater, particularly the punches or *'terebra lancinata'*, *'modiolus'* with big or long teeth and many others that he described. The optimal drilling head should not have long cutting teeth and should be wider on the proximal end than on the distal one. He then continued talking about the handles. He described in first place those straight handles that were moved by strings, with different acceleration mechanisms that had long been known. However, he criticised them due to their excessive weight, size and noise they made.

Finally, d'Acquapendente described the instrument that he had designed himself after all these considerations. He thinks it solves all the problems and that it only has advantages. However, it is similar in all aspects to those described by other authors. Even the description of the instrument is a bit confusing as he states the following: 'I have invented an instrument or trepan with round toothed saws that were called modiolus, punch or terebra in Latin. The lower part of the instrument (which is the one that drills the bone) is called modiolus and has four wings. The upper part that spins is the handle of the punch'. The instrument was neither too heavy to sink, nor too light to make the intervention difficult. It made no noise and was handled by the surgeon's hand, according to his words. This instrument was shown in his work and it was called *'trepan'* in the edition of 1658 and *'trypana'* in the edition of 1666. It had a T-handle or *'manubrium'* and two hollow cutting crowns with a truncated cone shape, a grooved surface and serrated edges. The male version had a central pin, which was missing in the female one.

The trepanation started by opening the wound and enlarging it if was necessary. It was filled with threads and feathers that are soaked in warm wine. The male trepan was used later. It was firmly held with the left hand so that it did not move whereas the right hand made it spin. It was substituted by the female trepan, which was lubricated and cooled whenever it was necessary. Once the bone had been cut in depth the skull disc was lifted with a small lifter and removed with some forceps.

As we have already mentioned, d'Acquapendente accurately described another ten interventions of the head in his work. Among them, we would like to highlight a great amount of vessel ligations and cauterisations, particularly on the bregmatic area. They aimed to treat different types of headaches and remind us of the 'sincipital mutilations' of primitive cultures.

13.3 Spanish Surgeons: Alcázar, Arceo, Montemayor and Daza Chacón

Among a great number of eminent Spanish surgeons, we would like to highlight those who were more relevant in cranial surgery such as Andrés Alcázar, Daza Chacón, Cristobal Montemayor, Francisco Arceo or Juan Fragoso.

The Spanish surgeon Andrés Alcázar (c.1500–1584) published in Latin his only book titled *'Chirurgiae libri sex: in quibus multa antiquorum et recentiorum sub obscura loca hactenus non declarata interpretantur'* in 1575 [15]. This work was commented by J.M. López Piñero and L. García Ballester, who were in charge of the translation into Spanish that we have consulted [16]. Book 1 is about cranial injuries and, therefore, cranial trepanation, which Alcázar supports. Alcázar adapted the indications thereof and improved the technique of that time. Following the style of that time, the book is organised in chapters reviewing the different types of lesions. Chapter IV is about 'The diverse signs of penetrating wounds of the head'. Chapter V is about 'The signs of injured membranes of the brain'. Chapter VI addresses 'The signs of an incision on the brain substance'.

Finally, Chap. XV is about trepanation under the title 'If the bone should necessarily be drilled in those cases with a penetrating wound on the head', showing the arguments for and against trepanation. Alcázar distinguishes between wide and narrow linear fractures. The former did not require trepanation as the humours could come out of the margins of the wound, whereas the latter might require trepanation as the drugs cannot penetrate and the pus cannot come out of them either. Trepanations should not be done immediately, when there are no symptoms. They should not be carried out many days after the symptoms have appeared. Both actions would be incorrect and risky. He highlighted the three classical indirect diagnosis methods of a fracture: black ink over the bone, tapping the skull with a probe that makes a hoarse or a muffled sound similar to a broken pot, and finally the grinding of the teeth, where the patient had to hold a guitar string or copper thread between his or her teeth. The string was tapped and, in those cases, where the bone was broken the injured patient could not bear it without grinding his or her teeth.

Another Spanish surgeon who was involved in trepanation practices and contemporary of Andrés Alcázar was Francisco Arceo (1493–1580). He was born in Extremadura (Spain) and worked for many years at the hospitals of the monastery of Guadalupe, where there was an important school of surgeons. He published in Latin his work *'De recta curandorum vulnerarum ratione'* at a very old age (just like Alcázar) in 1774, 6 years before his death. His work was widely distributed throughout Europe and was translated into English, French, German and

Dutch. He was a strong supporter of trepanation and described a trepan similar to a straight shank with two crowns, one on each end. It worked by making it spin between the palms of both hands (*'modiolus nespulatus'*). According to the translation carried out by A. Chinchilla, he accurately described the use of the trepan in his works as follows [17]. The trepanation is carried out on the third day. The male crown is placed first perpendicular to the skull and the surgeon made it spin until it penetrated through a thickness similar to the edge of a coin. Then he uses the female crown, which has exactly the same diameter. It is spun carefully. The cut made with it was carefully observed when reaching the internal table. If the internal table was already broken in some points, the crown was bent to complete the cut of the other part of the circle, leaving a free bone fragment that was removed with the most suitable instrument and without injuring the brain membranes. Once this was done, the lenticular knife, which was heated up with a fire, was used to remove all unevennesses of the bone so that the dura mater would not be injured with them. He also recommended trepanning on the third day in those cases with fractures caused by a sword or cutting objects.

Arceo, who was a firm believer in trepanation, affirmed that 'I think there is no safer procedure than trepanning. No dangers can be feared concerning trepanation, even when there are no important injuries inside. I repeat, there is no danger. The intervention should not be delayed because if not enough attention is paid it can result into an immediate threat and even a sure death. Some surgeons thought that scrapping the bone until the fissure disappeared was enough. However, they were wrong. Although they feel confident with the intervention, the patients start showing fatal signs that lead to death and nobody can be saved'.

Cristóbal Montemayor (ca. 1570–ca. 1613) studied medicine at the University of Valladolid (Spain) and was the surgeon of kings Felipe II and Felipe III. He published a book titled *'Medicina y Cirugía de Vulneribus capitis'*. The book was a commented translation into Spanish of book III from the Corpus Hippocraticum [18]. His comments included the clinical experience and the doctrines on the subject that prevailed in the sixteenth century. He supported trepanation but only in those cases when its indication had been proved and the surgeon had enough technical knowledge. He criticised, thus, the indiscriminate practice thereof.

Finally, Dionisio Daza Chacón (1510–1596) was a well-known Spanish physician and surgeon who was born and trained in Valladolid and Salamanca. He worked as a military surgeon under the orders of the kings Carlos V and Felipe II. Along with Andreas Vesalius, he cared for the cranial trauma of prince Carlos, son of Felipe II. He started writing at an old age, just like many physicians of that time. When he was 70 he published his great work *'Práctica y teórica de cirujía en romace y en latín: primera y segunda parte'* in 1580. It had many re-editions [19]. The second part of the work focuses on head injuries and lesions. One of its chapters is particularly aimed at classifying and describing the instruments required for a cranial surgery. The edition of 1626 that we have consulted, however, has no illustrations. Daza Chacón pointed out in the chapter *'De las herramientas para obrar en las fracturas de la cabeza'* [On tools to be used for head fractures] that probably so many instruments have been invented for cranial surgery that it is impossible for the surgeon to have them all. He wisely affirmed that it was not known how Hippocrates' instruments were like but stated that ancient and also modern surgeons had 'terebra, modiolus, scalpri, saws, lifters, lenticulars, mallets, pincers with different shapes and compositions'.

Daza Chacón says that there were two different types of terebra. Those with the shape of a punch were dangerous, as Hippocrates had already pointed out. He stated that surgeons after Celsus added to them a ring above the tip so that it could not dip inside the skull and that Galen called it *'abaptista'*. He said that these terebra were used to make several holes on the skull that were later connected with the lenticular and tapping with a mallet. In any case, the terebra should not be used in thin bones, in fragmented bones or in children. Now Daza Chacón introduces the cutting with saws. Saws, he says, could be straight or circular. Daza Chacón said that he had never used straight saws for the skull. However, he had used them 'many and multiple times' in long bones to carry out amputations or fragment resection of long bones. When talking about the circular or round saw (trephine crown), Daza Chacón introduces a semantic chaotic confusion at this point as he literally wrote: 'It is called in Greek Trypanon or Chinicion or Chinicidian. However, Avicena called it Anichades, so the term became corrupted. Cornelius Celsus called it Modiolum and Hippocrates called it Serra teres and Serra circularis, but we call it Trepano'. He points out that there were two types of circular saws. One was called 'the male' and the other 'the female', and he states that the central pin or nail, that he calls *'guion'*, could be added or removed. The instrument had a handle that could be used with just one hand. Circular saws with different diameter were interchangeable as they could be embedded in the handle and fixed to it by a screw. Daza Chacón mentioned that 'this instrument is the very best among all those that have been invented. Hence, they say that it is saintly and safe and cannot be compared to any other'.

After the description of those perforating instruments, Daza Chacón describes other instruments used by ancient surgeons, such as chisels (*'scalper'* in Latin), that could be flat or grooved. They were used to erode or cut the bone, to make holes on the skull instead of using the trepan. He pointed out that modern chisels were called curettes and that they were very safe to scrape the fractures and, if required, to penetrate through the cranial bone. Curettes might have a different width and allowed to pierce the bone so that 'any waste that was over the membrane could easily come out and apply the medicines that might be necessary'. A particular type of curette was the lifter. Lifters allow to lift bones that compress the dura mater, although they can also be lifted with punches or pincers. Finally, a third type of curette was the so-called lenticular, which was called *'scalper lenticulatum'* and *'lenticulum'* in Latin and *'phacotus'* in Greek. Danza Chacón also praised this instrument 'due to the safety it involves when working with it as there is no way the dura mater can be injured'. He also mentioned that, according to Galen's words 'no harm can be done even if you use it while you are asleep'. Finally, he mentioned the *'scalpros excisitorios'* which were used for bones fragmented in many pieces. However, Daza Chacón pointed out that he preferred to remove them with a pair of big scissors.

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14 Other Relevant European Surgeons in Trepanation over the Sixteenth and Seventeenth Centuries

During the sixteenth and seventeenth centuries the contributions by British and German authors were less relevant than the Mediterranean authors described in the last chapter. In this chapter, we are going to describe the recommendations and instruments by the British authors Peter Lowe, John Browne and Richard Wiseman, and the German authors Hans von Gersdorff, Walter Herman Ryff, Wilhelm Fabry and Johannes Scultetus.

Previously, when reviewing the professional activity of physicians and surgeons in Scotland, we have mentioned Peter Lowe (1550–1612), who was the founder of the Faculty of Physicians and Surgeons in Glasgow in 1599. Lowe also had a significant role in cranial surgery of that time [1]. Lowe was a catholic physician born in Scotland. He was trained in Medicine in France, where he worked and served in the Spanish and French armies. He went back to Glasgow at the end of the sixteenth century. He wrote his greatest work *'The whole course of chirurgie'* in 1597. It was probably the first general work on surgery that was written in English. Concerning cranial wounds, he pointed out that lifting a fracture, whenever it is possible, is a better option than trepanation, which must be carried out in the suitable places and avoided in children. The book was published in 1597 and later edited several times, when illustrations were included and the title was modified (Fig. 14.1). In a plate titled *'A trepan, with other instruments for the head'*, the instruments of trepanation are collected, specifically a trephine crown with central pin and braking system, affixed in a brace-like hand. An exfoliating pointed piercer is shown next to it. In the upper right corner there is a triple-legged instrument, with one of them ending in a thread like the *'tirefond'*, another in the form of an elevator and the last pointed. The plate depicts some vertical instruments that are, from left to right, a bone saw, a *'rugine'*, a strong bone clamp, a lenticular knife, a dura mater depressor and a punch. Below, to the right, Lowe represents a dried skull with two trepanations [2].

The trepanation technique included the general and common preparations to adjust the head and fix it, plug the patient's ears and light a fire in the room to prevent the cold air from contacting with the membranes (dura mater). Lowe says that to carry out a trepanation the crown with a central pin is used in first place. It will immediately be removed. Then the surgeon continues with the trepanation until finding the diploe. After that, he cut the internal table. The inclination of the crown must be rectified in that moment when applicable to cut all the internal table without injuring the dura mater. The disc of bone is finally removed with a three-legged *'tirefond'*.

John Browne (1642–1702) was an interesting English figure and surgeon. He had serious problems with the management of the St. Thomas's Hospital in London, where he worked. He was accused of signing works written by other

J. M. González-Darder, *Trepanation, Trephining and Craniotomy*,
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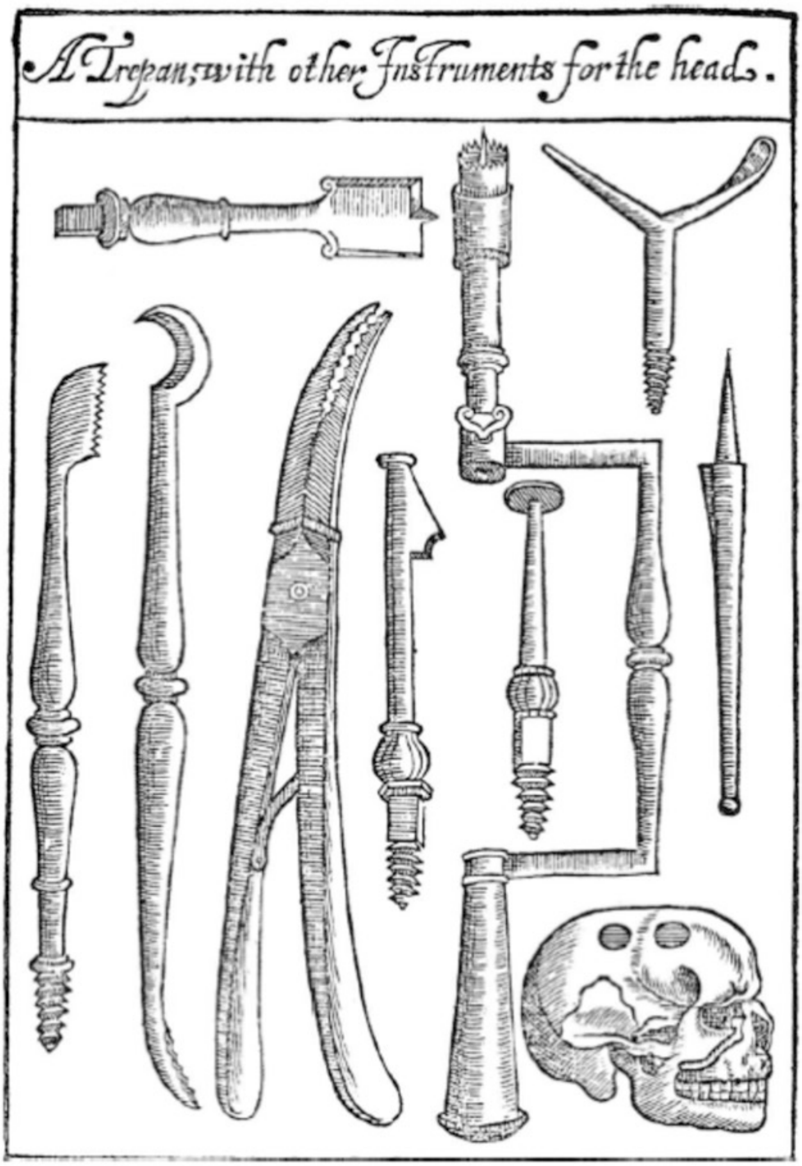


Fig. 14.1 Instruments related to trepanation by Peter Lowe (Lowe P. The Whole Course of Chirurgerie. London: Thomas Purfoot; 1597)

authors. He published the book *'A Complete Discourse of Wounds'* in English in 1678 [3]. It included several chapters on head wounds. He entitled Chap. XXV *'Of Incision of the Hairy Scalpe and Opening the Skull'*. He followed Hippocrates' ideas in almost all his remarks and when describing the surgical technique. According to Brown, the indications and aims of trepanation were the following: to remove the fragments of weapons or bones, to reduce and place back to their original position the depressed fragments of skull, to remove the blood and clots between the bone and the dura mater and finally to adequately apply the medicines on the wound and the fracture.

In the first part of the book by Browne there are a large number of chapters dedicated to the wounds and fractures of the head and their treatment, with some plates where the surgical instruments are collected (Fig. 14.2). The description of the figures is on the text. The described instruments for trepanning were limited to the *'capital*

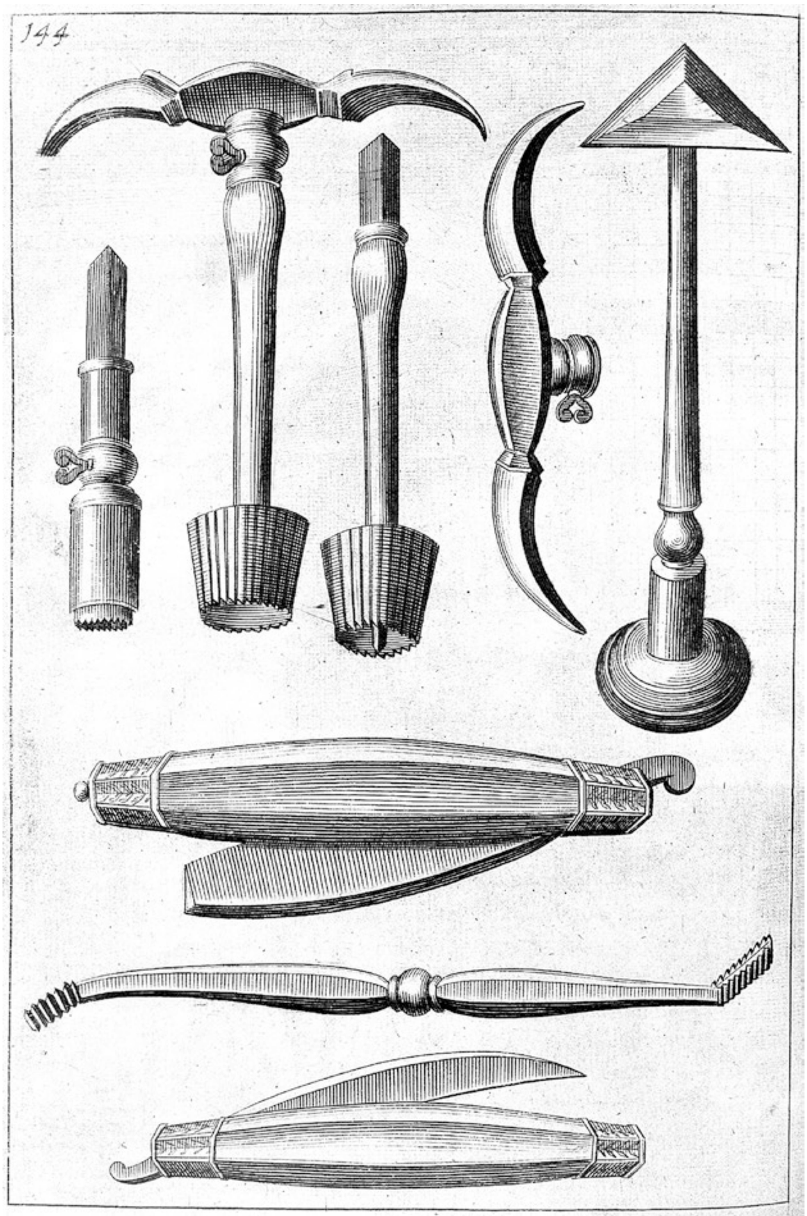


Fig. 14.2 Instruments related to trepanation by John Browne (Browne J. A compleat discourse of wounds. London: E. Flesher; 1678)

saw', 'raspatories', 'levatories' and *'trafine or trepan with heads'*, which were also illustrated in a print. In the upper line of the plate dedicated to illustrate the trepanning instrument are represented two types of perforators, which he names interchangeably *'trafine or trepan'*. On the left there is a perforator type *'modiolus'* with a hollow cylindrical crown and an external stopper in the form of adjustable height crown. Next to it there are two hollow conical perforators with a grooved surface, one of them with a central pin. The handle is on 'crane wings' design and drills are interchangeable on its tip. On the far right is an instrument called by Browne *'capital saw'* or scraper. Underneath are two knives, one cutting and one shaving, and between them a double-ended instrument, on one side finished in a thread in the manner of the *'tirefonds'* (*'levatory'*) and in the other slotted as a scraper ('*rasperatory*').

Richard Wiseman (c.1621–1676) was an English surgeon, surgeon of King Charles II and author of the books *'A treatise of Wounds'* published in 1672 and *'Several Chirurgical Treatises'* published in 1676. In these books he gathers his experience in the treatment of head injuries, based on the treatment of war wounds. The text is clear, systematic and concise, and is accompanied by many clinical cases described vividly. We have reviewed the management of head injuries explained in the sixth edition of the second book, where they are described in '*Chap. IX Of Wounds of the Head*' [4]. The cranial lesions are described according to the different structures involved, after defining the different anatomical levels from the scalp to the ventricles. It recognises that the accumulation of blood and other fluids between the bone and the dura is possible, even in cases where there is no fracture. (*'Sometimes, very small Fissures, how inconsiderable so ever they may seem, are the Cause of the Patient's Death; There being often found extravasated Blood upon the Dura Mater, and the Veins broken, either by the Concussion from the Blow, or by the rough Edges of the inner Table. Therefore, you are to consider the Symptoms, and accordingly lay the Wound either'*). However, Wiseman is quite conservative in the indication of trepanation. Thus, if the fracture is wide, fluids can be released spontaneously and there is no need to trepan *('I know it will be hard to dissuade some Chirurgeons from applying to Trepan in this Case: for I myself have been glad to complied with some of them, in setting on a Trepan where the Fissure was sufficiently large, … But what did it mean? Indeed, where the Fissure lieth untowardly for Discharge of Matter, or where the Depression of the Cranium is deep, there is a Trepan ought to be timely applied')*.

Wiseman describes succinctly the technique of trepanation in this way: *'In order to the Perforation of the Cranium, the Bone must be clear'd of its Pericranium, lest in setting on the Terebra or Modiolus, (which are two several Names for to Trepan,) … When you have set on your Trepan, press on it with your Left Hand, and turn it round with your Right. You must use a little ol. ros. or Milk to cause it to move the easier, and as it fouls, brush it; in doing of what, it will be cool. Before you approach to the second Table, (which you may know by the Blood that appears) it will be requir'd that you take out the Pin, and proceed more warily, not listening to the Prattling of the Standers-by, but often lifting up your Hand, lest by your Compression or Haste you unawares fall upon the Dura Mater, and wound it. Some Chirurgeons do bring out the Bone in the Bore; but it will be safer to raise it up with your Levator, … During this Work, it is fit the Patient's Ear were stopped with Lint, lest the Noise disturb him. The Room ought also to be close. The Perforation made in Cranio, and the Bone taken out, you are to smooth away the Asperity which remains in the lower Table, by the Lenticular Instrument made for that Purpose. If after this the Membrane be foul'd by the Sawsdust of the Bone, you must wipe it off with a soft Sponge, or a little Lint upon your Probe. The Part on being cleans'd, you are to dress up the Membrane'*. Then Wiseman explains how to expand the cranial opening by doing an additional bone resection. However, he severely criticises surgeons who remove too much bone. (*'If the Opening in the fractur'd Cranium be not sufficient, make one in the most declining Part, and raise up the Bones, and free the Membrane of whatever may offend it. But do not take out more Bones than needs must: Like some of those Chirurgeons I have met, carrying them about in their Pockets, boasting in that which was their Shame'*).

However, Wiseman is aggressive in the exploration below the dura mater. He says that in case of bad evolution and not finding any injury, fracture or accumulation under the bone, it is necessary to suspect that there is an injury below the dura mater, the pia mater or even in the ventricles. Unfortunately, in these cases, even if there is a fracture, there is not much to do and the prognosis is usually ominous (*'… leave it to Nature, lest the Patient die under your Hands, …'*). He then describes 17 clinical cases and adds an addendum about lesion of the brain (*'An Additional Discourse of Wounds of the Brain'*), where he is definitively pessimistic about these injuries ('*At Sea, those wounded into the Brain die soon; we have no Conveniency of lodging them- or dressing* *them, so warm as they require. In the Wars, my employment did not allow me to finish the job of the Cures; and here, in my Practice in and about The City, I never was call'd unto any so wounded, where there were any Hopes of Cure; therefore, must leave that to others to treat of'*).

Besides all of these recommendations on surgical practice, it is interesting to comment the singular anatomical relation that Wiseman establishes between the pericranium and the dura mater, since he considers that they are in continuity through the sutures. In fact, he says that it is the sutures that divide the skull into several bones and these anatomical relationships explain some problems and complications of head injuries ('*The Pericranium arising from the Dura Mater through the Sutures, by which Continuity that may also be part of the Inflammation*').

We have presented above the German surgeon Hans von Gersdorff (1455?–1529) when studying the *'tripolides'*. This surgeon was born in Strasbourg but the place where he was trained is still unknown. He was an anatomist and practised by dissecting the corpses of people who had been executed. He also worked as a surgeon in the army and was involved in many battles. He was the author of the first book on anatomy and medicine which was written in German and published in 1517 [5]. Its name was *'Feldbůch der Wundartzney'* and it was based on the books written by Guy de Chauliac. Gersdorff became specialised in amputations. In fact, his book shows the first amputation ever illustrated. He also described the already mentioned instrument with three legs and a similar one that had two legs and resembled a press (torcula). The text comes with two vivid illustrations made by Hans Wechlin showing the faces of the patients that underwent a treatment with the instruments. The patients show neurological deficits on their faces, particularly a forced abduction of the right eye that is ipsilateral with respect to a cranial fracture. It was presumably due to a paralysis of the oculomotor nerve and it was accompanied by a contralateral facial paralysis. The illustrations shown in later editions were beautifully coloured by hand (Fig. 14.3).

Walther Hermann Ryff (c1500–1548) was a character with a controversial biography, as he was a doctor and surgeon but there is no evidence that he trained in these fields. It seems that he worked as a pharmacist. He published numerous books on pharmacy, medicine and surgery, which were very popular in Europe. He was accused of plagiarism at the time. He has also been considered a successor to Hieronymus Brunschwig in Strasbourg, but this fact is not proven either, since although he was born in Strasbourg he never lived in that city again. The book *'Gross Chirurgei'* was written in German and shows instruments for cranial surgery (Fig. 14.4). He describes perforators type *'terebra'* mounted in T arms (page XXX) or type *'torcula'* with supports of two or three legs (pages XXI and XXXII).

Also, in mainland Europe, Wilhelm Fabry (1560–1634), also known as William Fabry, Guilelmus Fabricius Hildanus or Fabricius von Hilden, was an interesting German surgeon who was born in the town of Hilden. He learnt German, French and Latin when he was a child and Greek and Hebrew later. He started learning surgery when he was 15 years old as an apprentice. He studied anatomy later and became a barber master in Cologne in 1599. He travelled across Germany and Switzerland and published a great number of books. As an anecdote, he married Marie Colinet, a skilled obstetrician and surgeon, in Geneva in 1587 [6, 7].

His most interesting book was *'Opera observationum et curationum medico-chirurgicarum quae extant omnia'*, a compilation of 600 clinical cases or commented observations. The first 25 observations were published collected in 1598. Then, the cases were published in groups of a hundred (*'Centuriae'*) between 1610 and 1620 [8]. They were spread all together for the first time in 1641. The book contains several illustrations on cranial surgery and instruments (Fig. 14.5).

He described four cases of depressed cranial fractures in adults and their evolution after lifting the fragments in Cent.II, Obs.III. Case I reads as follows: 'A 40-year-old nobleman was hit by an iron piece that weighed 1.5 pounds on the left side of bregma. It caused the poor man a depressed fracture. The patient fell to the ground as if he was dead and had speech, visual and hearing loss. It was followed by a paralysis attack on the opposite side to the blow. Some days after lifting the skull he recovered speech and all the symptoms improved subsequently until he completely recovered his health condition'. He described an instrument that he called *'elevatorium'* in Cent.II, Obs.IV (*'De elevatione cranii, pracipue in adultioribus aucta & emendata'*). It was used for treating depressed fractures. The instrument, a crane's elevator and all its parts, is drawn and described in great detail in page 80: A. It indicates the fork's fork, for easy handling by hand; B. opening to make way for the bar; C. tip of the elevator, which is stuck in the skull, in a hole made with a *'terebelum circumducendum'*, with triangular or quadrangular tip, which is drawn on the same page; D. support for the head; E. screw to raise and lower the elevator as required by the surgeon; F. twelve inches elevator bar (*'pollices duodecim'*); G. articulation. On page 81, the use of the elevator on a patient's head is illustrated and a hook-shaped attachment is drawn to lift loose fragments of bone. On the same page a saw is drawn, tweezers and some swabs or sponges. On page 82 there is another perforated elevator attachment, which is used to

Fig. 14.3 Torcular instruments and surgical technique described by Hans von Gersdorff (Von Gersdorf H. Feldtbuch der Wundartzney. Strasbourg, 1517)

Fig. 14.3 (continued)

ensure the elevation of the fragments, as it is drawn applied on the head of a patient. On the same page, a new elevator is drawn, and below it describes a new clinical case. Finally, in page 80 a *'terebelli'* is drawn mounted in a brace handle and in page 83 there is a *'terebellum'* mounted in a T-handle.

He described depressed fractures` of children (ping-pong fractures) in Cent.II, Obs.V (*'Puerorum depressum cranium, quamodo elevandun'*). He also explains and draws in page 84 how to reduce them by lifting them with an adhesive paste and a rope or, if it failed, by inserting a *'terebellum'* with a spiral threaded end sim-

Teutschen Chirurgei. XXX

dann einn kurtzen bericht aller Chirurgischen Operation/zu gemeyner einleytung der anfahenden Schůler oder Discipel der Chirurgei setzen wöllen.

Zu obgemelter wirckung die zuuolbringen/seind auch in sonderheyt ettliche Instrumentlin/so mann Proben nennet/von nöten/damit zu probieren oder erkündigen die tieffe eines schadens. Deßgleichen damit zu fůlen vnd sůchen/wo solche geschoß ligen. Solcher Pröblen mag mañ auff dreierley art haben/wie sie hie verzeychnet seind.

Die erst ist võ weychem eisen bereyt/damit sich auch vnderweilen gebogen werden mag/nach erheyschung der notturfft. Solcher Proben soltu grosse kleine vnd mittelmessige haben/wie es dann mancherley notturfft erfordert.

Die ander/so krumb hin vnd wider gebogen in der mitte steht/die magst du dir selbs nach deinem gefallen bereyten zu tieffen krummen holen fisteln/damit mancherley krummer hölin oder gäng der selbigen zuersůchen. Dann das Blei mag sich nach art solcher krümme hin vnd her biegen. In der notturfft magstu ein langes dünnes Wachskertzlin nemen/dañ so dasselbig warm ist/beugt es sich auch aller massen/wie dises bleien pröblin/wie du es auch hieoben zu aller vnderst verzeychnet sihest.

Nechst disen Probmeysseln oder Sůcherlin folgen die nadeln vnnd rörlin/sampt anderm hefftgezeug/Von welchem wir droben in beschreibung der fürnembsten wirckung/so dem Chirurgo zůsteht/kurtze meldung gethon haben/mit vnderrichtung mancherley art der hefftung. Magst auch hieruon weiter ein besonder Capitel lesen in folgender Chirurgei.

Vber dise oberzelte gemeyne Instrument/so hin vnd wider an mancherley orten des leibs/nutzlich in vilfeltiger Chirurgischer wirckung gebrauchet werden/seind noch andere/so etlichen glidern in sonderheyt zůgeeygnet seind/als nemlich/dise hieneben gesette hauptstuck/damit im bruch der hirnschalen das gebrochen bein zuboren/vnd auffzuheben. Solche Instrumẽt seind bei den alten gar schlechtlich gemacht gewesen/nemlich/auff dise weiß/wie du sie hieneben verzeychnet sihest/bei jnen Trepana genant. Dise form haben sie jeder dreierley art gehabt/als groß/klein vnd mittel. Doch magstu solche Instrument allein in dem schreublin vnden enden/

Fig. 14.4 Instruments related to trepanation by Walter Herman Ryff (Ryff WH. Gross Chirurgei oder volkommene Wundarznei. Francfort/Main: Christian Egenolff; 1559)

Fig. 14.4 (continued)

Erſte Theyl der

enden/welchs mañ abwechß-
len mag / gleich wie in den
ſcharpffbörerlin/ damit mañ
die büchſenkugeln auß/chrau
bet. Zu diſen Inſtrumenten
braucht mann / ſolche gebro-
chen bein auffzuhebē/diſe hie
neben geſetzte Inſtrument/
vnder welchen das mittelſt
auch dienet / bein zubrechen/
vñ ſchneidē. Aber das oberſt
nennet mann Separatorium,
ſo mann mit den obgeſetzten Inſtrumenten durchboret hat/daß mañ es dann
ſchneide von einem loch zum andern/dann mag manns mit dem vnderſten In
ſtrument auffheben/ꝛc.

Aber diſer zeit ſeind diſe hernach folgende mehr im brauch / wie du ſie nach-
einander geſetzt ſiheſt.

Diſes erſt Inſtrument dienet oben auff
das haupt/die hirnſchal damit zuboren/ vñ
die gebrochnē bein damit außzuhebē. Oder
wo ſie von hartem fallen/ſchlagen/ vñ der-
gleichen/hineinwertz gebogen wer/ dz mañ
ſie damit widerumb herauß ſchraube. An
den vnderſten gleychlin ſollen die bereyten
blechlin mit zartem filtz wol gefüttert wer
den/durch die löchlin ſolcher blechlin ange-
hafft/damit es auff dem gſchedigtē haupt
deſto weniger beſchwernüß bringe.

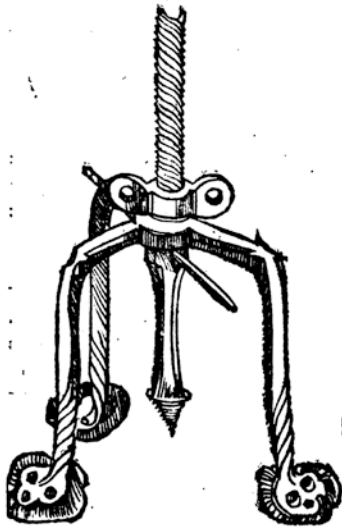
Hie merck auch/daß die ſchreublin inn di-
ſen Inſtrumenten ſehr ſcharpff ſein ſollen/
damit ſie on groſſe mühe hinein geſchraubt
werden mögen/vnd auffs aller ſanffteſt.

Diſes vnderſt hienebengeſetzt Inſtrumēt
dienet mehr beineben des haupts/darūb ſei
ne blechlin etwas breyter ſein ſollē. Dienet/
wie von dem nechſt vorgeſetzten geſagt iſt/
die hirnſchalen durchzuboren / die gebroch-
nen bein auffzuheben/ vnd die eingeſchlagē
oder eingfallen hirnſchalen damit widerūb
herauß zuſchrauben. In

Fig. 14.4 (continued)

Teutſchen Chirurgei. XXXI

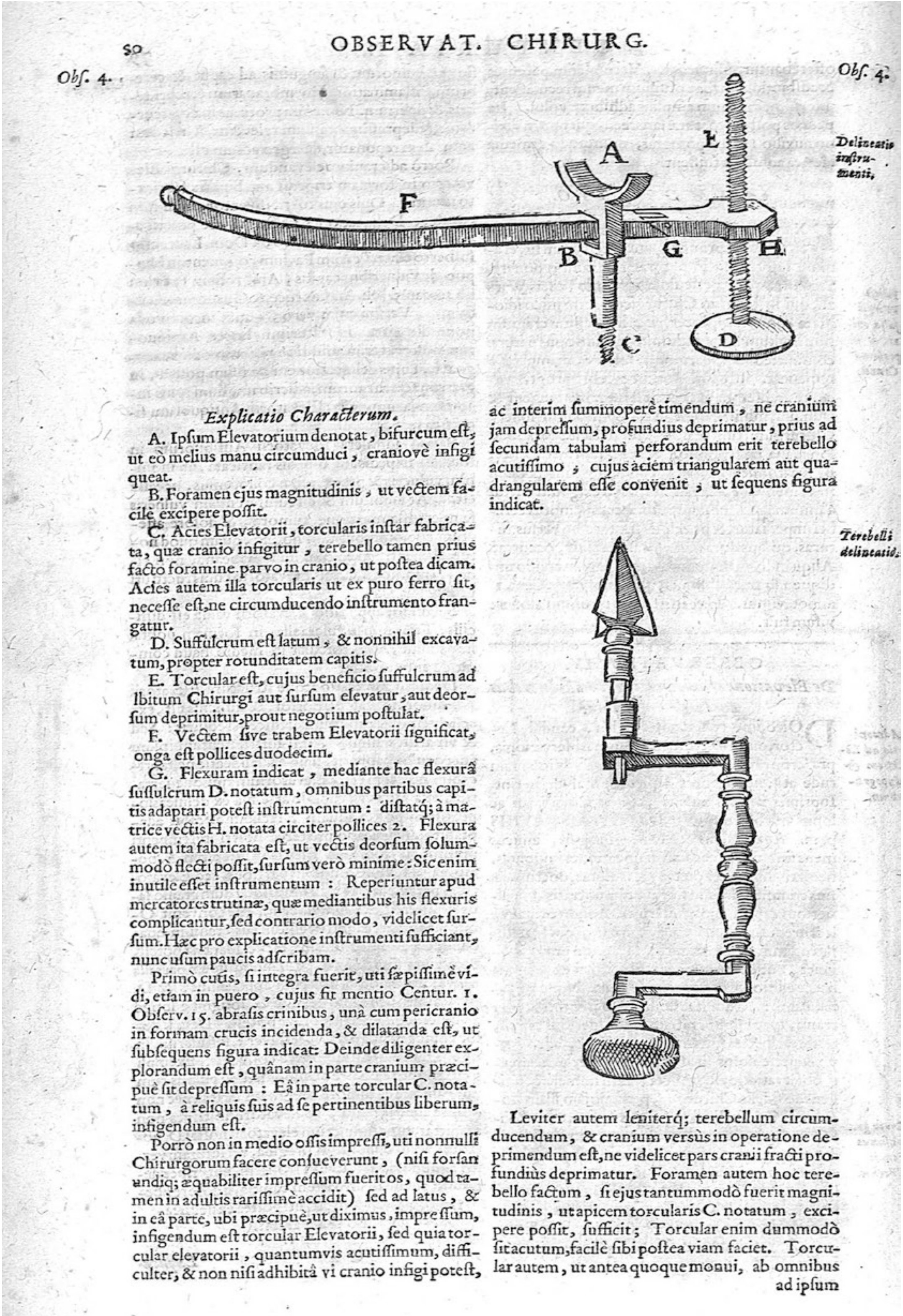
In diſen beiden Inſtrumenten ſiheſtu wie alle ſtuck in beſondern gewerb-
lin oder gleychlin gehnd/welches dermaſſen alſo verordnet/daß manns weit
oder eng machen kan/nach dem der ſchade/ oder ſolcher bruch der hirnſchalen
einn groſſen begriff vmbſich hat/Wie dich dann der gegenwertig zů fal in ſol-
chem allem wol wirt vnderrichten künnen.



Diß hieneben geſetzte Inſtrumēt iſt auff
die gemeyn Nürnbergiſche weiß/ on gleych
lin/bereyt/ Mag in der notturfft / wo der
ſchaden nit zugroß/auch in ſonderheyt nutz
lichen gebraucht werden/in aller obgemel-
ter weiß. Noch ſeind etlich newe Inſtru-
ment/von Italianiſchen Chirurgis erfun-
den/welche in ſicherheyt diſe alle vbertref-
fen / derē rechte warhaffte Contrafactur/
ſampt jrem vilfeltigē nutzlichem gebrauch/
haben wir als einn beſondern ſchatz/ſampt
andern vilen dergleichen nutzlichen Inſtru
menten/ ſo den Teutſchen Chirurgis noch
vnbekant / in das letſt Theyl diſer vnſerer
groſſen Teutſchen Chirurgei behalten / di-
ſes orts allein / wie auch von andern ſtucke
zum offtermal angezeygt / diſe ſtuck zu ge-
meyner einleytung der angehnden Wundt-
artzet hieher geſetzt/rc.

Dieweil aber diſe wirckung / nemlich die
gebrochnen bein der hirnſchalen zuziehen/
oder die ſelbigen in der notturfft zubrauchen / vnder allen fürnembſten wir-
ckungen der Chirurgei/der aller gefehrlichſten eine iſt/wil mich beduncken vō
nöten ſein/hierinn etwas weitläuffigern bericht zuſetzen. Dieweil nun ſolche
wirckung faſt ſchwerlich/ſoltu mit deſto gröſſerm fleiß ſolche vnderrichtlig be
trachten/damit auß deinem vnuerſtand niemandt verwarloſet werde. So du
nun mit obgemelter Inſtrument einem die hirnſchalen durchboret/ vnnd das
bein ſo hinweg hat müſſen/hinweg genommen haſt/vnd die bort der hirnſcha
len von aller ſcherpffe wol geebnet iſt/damit hernach von ſolcher ſcherpffē die
Dura mater, das iſt/das ober gröber hirnfellin nit verletzt werd/ vñ die wund
groß iſt/alſo/daß du ein groß ſtuck beins hinweg genommen haſt / in welcher
ſeiten des haupts das ſei/vnd der verwundt ſtarckes vnnd krefftiges leibs iſt/
vnnd gröſſer arbeyt gewonet hat. So ſoltu alsbald das fellin vnnd die gantz
wunde ſampt dem bein mit gůtem weiſſem krefftigem wolriechendem war-
mem wein ſauber abſpůlen vnnd reinigen von gelifertem blůt. Nach ſolcher
erwaſchung trückne ſie wol auß / vnd beſprengs mit gůtem gebrantem wein/
der künſtlich diſtilliert vnnd rectificiert ſei/vnnd verbinds mit dem gemeynen
hauptpuluer/welches alſo bereyt wirt: Nim bitter Aloes/Myrrhen/weiſſen
Weirauch/Drachenblůt/jedes ein quintlin/vermiſchs wol zuſamen zu eim rei
nen puluer. Oder magſt diſes hauptpüluerlin auff ein andere art bereytē/da-
mit es das hirnfellin baß krefftige/ Nim Myrrhen zwey lot/bitter Aloes ein
halb lot/Sarcocolle/weiſſen Weirauch/Drachenblůt / Ferberröte/ der ſchö-
neſten Scharlachbeer/jedes zwen ſcrupel/vermiſchs zuſamen/ vnd brauchs in
die wund mit faſen/alſo bereyt/daß es das gantz bein bedecke/ Dann leg jhm
pflaſter von diſem koſtbarlichen hauptpflaſter auff/welches die gantze wund
allenthalben wol begreiffe. Diß pflaſter bereyt alſo: Nim wolzeitig Roſen-
öl/vnzeitig Roſenöl/das iſt von grünem vnzeitigem Baumöl bereyt/acht lot/
Kelbern fett/Hammels fett/jedes fünff lot/gelb geleutert vnd geſottē Spi-

ß



50 OBSERVAT. CHIRURG.

Obſ. 4. Obſ. 4.

Delineatio inſtrumenti.

Explicatio Characterum.

A. Ipſum Elevatorium denotat, bifurcum eſt, ut eò melius manu circumduci, craniovè infigi queat.

B. Foramen ejus magnitudinis, ut vectem facilè excipere poſſit.

C. Acies Elevatorii, torcularis inſtar fabricata, quæ cranio infigitur, terebello tamen prius facto foramine parvo in cranio, ut poſtea dicam. Acies autem illa torcularis ut ex puro ferro ſit, neceſſe eſt, ne circumducendo inſtrumento frangatur.

D. Suffulcrum eſt latum, & nonnihil excavatum, propter rotunditatem capitis.

E. Torcular eſt, cujus beneficio ſuffulcrum ad libitum Chirurgi aut ſurſum elevatur, aut deorſum deprimitur, prout negotium poſtulat.

F. Vectem ſive trabem Elevatorii ſignificat, onga eſt pollices duodecim.

G. Flexuram indicat, mediante hac flexurâ ſuffulcrum D. notatum, omnibus partibus capitis adaptari poteſt inſtrumentum: diſtatq; à matrice vectis H. notata circiter pollices 2. Flexura autem ita fabricata eſt, ut vectis deorſum ſolummodò flecti poſſit, ſurſum verò minime: Sic enim inutile eſſet inſtrumentum: Reperiuntur apud mercatores trutinæ, quæ mediantibus his flexuris complicantur, ſed contrario modo, videlicet ſurſum. Hæc pro explicatione inſtrumenti ſufficiant, nunc uſum paucis adſcribam.

Primò cutis, ſi integra fuerit, uti ſæpiſſimè vidi, etiam in puero, cujus fit mentio Centur. 1. Obſerv. 15. abraſis crinibus, unà cum pericranio in formam crucis incidenda, & dilatanda eſt, ut ſubſequens figura indicat: Deinde diligenter explorandum eſt, quânam in parte cranium præcipuè ſit depreſſum: Eâ in parte torcular C. notatum, à reliquis ſuis ad ſe pertinentibus liberum, infigendum eſt.

Porrò non in medio oſſis impreſſi, uti nonnulli Chirurgorum facere conſueverunt, (niſi forſan undiq; æquabiliter impreſſum fuerit os, quod tamen in adultis rariſſimè accidit) ſed ad latus, & in eâ parte, ubi præcipuè, ut diximus, impreſſum, infigendum eſt torcular Elevatorii, ſed quia torcular elevatorii, quantumvis acutiſſimum, difficulter, & non niſi adhibitâ vi cranio infigi poteſt, ac interim ſummoperè timendum, ne cranium jam depreſſum, profundius deprimatur, prius ad ſecundam tabulam perforandum erit terebello acutiſſimo; cujus aciem triangularem aut quadrangularem eſſe convenit; ut ſequens figura indicat.

Terebelli delineatio.

Leviter autem leniterq; terebellum circumducendum, & cranium versùs in operatione deprimendum eſt, ne videlicet pars cranii fracti profundiùs deprimatur. Foramen autem hoc terebello factum, ſi ejus tantummodò fuerit magnitudinis, ut apicem torcularis C. notatum, excipere poſſit, ſufficit; Torcular enim dummodò ſit acutum, facilè ſibi poſtea viam faciet. Torcular autem, ut antea quoque monui, ab omnibus

ad ipſum

Fig. 14.5 Instruments related to trepanation by Wilhelm Fabry von Hilden (Fabry von Hilden, Wilhelm. Opera observationum et curationum medico-chirurgicarum, quae existant omnia. Francofurti: J. L. Dufour; 1682)

CENTURIA II. 81

Obs. 4. ad ipsum pertinentibus partibus lib[erum]; clementer tam diu circumducendum est, usque dum cranio satis infixum fuerit: secundam tamen tabulam, quam vitream appellant Anatomici, perforare non licet, ne inde, ut fieri solet, fragmenta acutissima cranii, ad menyngas perveniant, easq; graviter lædant. Inter circumducendum autem & infigendum torcular, Chirurgus manum potius elevet, quam deprimat: omnibus enim modis, ne cranium cerebrum versus deprimatur; danda est opera. Infixo satis torculari, vectis Elevatorii F. notatus, traducendus est per foramen B. notatum, suffulcrum vero D. capiti imponere convenit, & quidem aptiori, minimeque dolore affecto loco. Ne autem caput è compressione suffulcri lædatur, latum, parumque excavatum esse debet. Linteum præterea aliquoties reduplicatum ut suffulcro substratum sit, necesse est. Suffulcri autem atque torcularis E. beneficio, tantum elevatur aut deprimitur vectis elevatorii, quantum Chirurgo necesse esse videbitur.

Omnibus sic ordine peractis, manu paulatim in altum elevandus est vectis F. notatus, donec pars cranii depressa sit elevata, & in situm naturalem reposita: in ipsa vero operatione, ut unus ex adstantibus caput firmiter teneat, necesse est. Negotium autem atque operationem, ut plenissime intelligant Tyrones, sequentem figuram adjungere visum fuit.

Accidit interdum quoque, ut pars aliqua cranii adeo sit fracta, ut ossa nonnulla absque labore digitis aut forcipe eximi possint, uti sæpissime in vulneratis observavi. Si itaque rima satis hians in cranio reperitur, tunc perforatione cranii, pro infigendo Elevatorio opus non est, sed sequenti

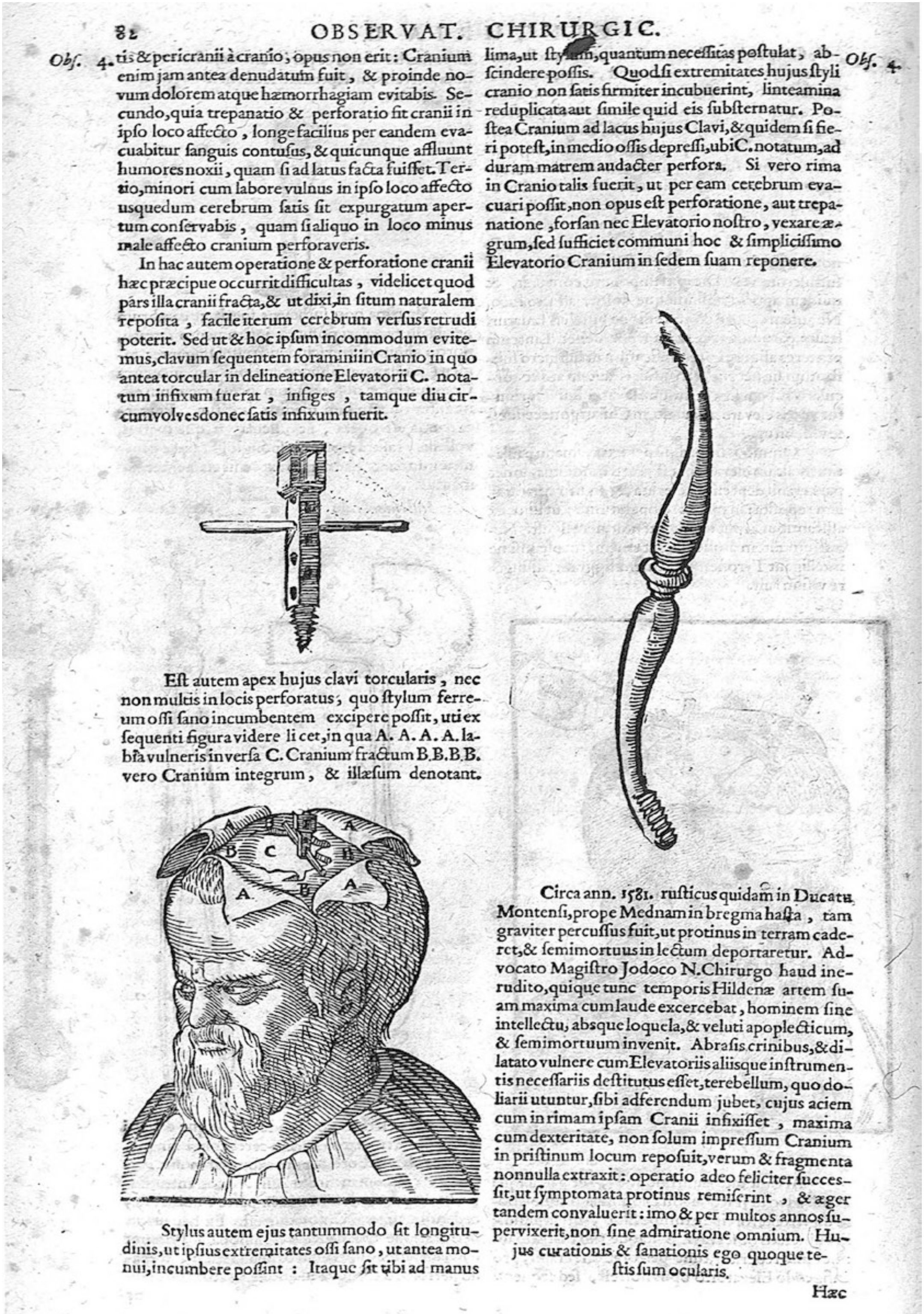
imposito hamulo, & per ipsum trajecto vecte F. notato, cranium depressum facile in situm naturalem elevabis. Obs. 4.

Sin rima non sufficiens fuerit, ut cerebrum per illam evacuari possit; instrumento serrato; portio aliqua ossis exscindenda est. Diligenter tamen (quod in omnibus operationibus, quæ circa Cranium fiunt, observandum) prospiciendum est, ne inter operandum meninx lædatur. Præterea danda est opera, ut officula, si qua fuerint, volsellis, rasura vero ossis spongiolis, aquæ betonicæ infuccatis, ac denuo expressis clementer eximantur.

Instrumentum Serratum. *Volsella.* *Spongiola.*

Quod si rima commode eò usque dilatari non potuerit, ut per eandem cerebrum à sanguine coagulato, ichore, & pure expurgari possit, perforetur cranium in medio ossis, quod antea depressum fuerat, nimirum ea in parte, ubi in præcedentibus figuris C. notatum est. Ex hac autem perforatione tria habebis commoda. Primum si os jam antea impressum & denudatum, trepano perforaveris, nova incisione, & abrasione cutis

Fig. 14.5 (continued)


82 OBSERVAT. CHIRURGIC.

Obſ. 4. tis & pericranii à cranio; opus non erit: Cranium enim jam antea denudatum fuit, & proinde novum dolorem atque hæmorrhagiam evitabis. Secundo, quia trepanatio & perforatio fit cranii in ipſo loco affecto, longe facilius per eandem evacuabitur ſanguis contuſus, & quicunque affluunt humores noxii, quam ſi ad latus facta fuiſſet. Tertio, minori cum labore vulnus in ipſo loco affecto usquedum cerebrum ſatis ſit expurgatum apertum conſervabis, quam ſi aliquo in loco minus male affecto cranium perforaveris.

In hac autem operatione & perforatione cranii hæc præcipue occurrit difficultas, videlicet quod pars illa cranii fracta, & ut dixi, in ſitum naturalem repoſita, facile iterum cerebrum verſus retrudi poterit. Sed ut & hoc ipſum incommodum evitemus, clavum ſequentem foramini in Cranio in quo antea torcular in delineatione Elevatorii C. notatum infixum fuerat, infiges, tamque diu circumvolves donec ſatis infixum fuerit.

Eſt autem apex hujus clavi torcularis, nec non multis in locis perforatus; quo ſtylum ferreum oſſi ſano incumbentem excipere poſſit, uti ex ſequenti figura videre licet, in qua A. A. A. A. labia vulneris inverſa C. Cranium fractum B.B.B.B. vero Cranium integrum, & illæſum denotant.

Stylus autem ejus tantummodo ſit longitudinis, ut ipſius extremitates oſſi ſano, ut antea monui, incumbere poſſint: Itaque ſit tibi ad manus lima, ut ſtylum, quantum neceſſitas poſtulat, abſcindere poſſis. Quod ſi extremitates hujus ſtyli cranio non ſatis firmiter incubuerint, linteamina reduplicata aut ſimile quid eis ſubſternatur. Poſtea Cranium ad lacus hujus Clavi, & quidem ſi fieri poteſt, in medio oſſis depreſſi, ubi C. notatum, ad duram matrem audacter perfora. Si vero rima in Cranio talis fuerit, ut per eam cerebrum evacuari poſſit, non opus eſt perforatione, aut trepanatione, forſan nec Elevatorio noſtro, vexare ægrum, ſed ſufficiet communi hoc & ſimpliciſſimo Elevatorio Cranium in ſedem ſuam reponere. *Obſ.* 4.

Circa ann. 1581. ruſticus quidam in Ducatu Montenſi, prope Mednam in bregma haſta, tam graviter percuſſus fuit, ut protinus in terram caderet, & ſemimortuus in lectum deportaretur. Advocato Magiſtro Jodoco N. Chirurgo haud inerudito, quique tunc temporis Hildenæ artem ſuam maxima cum laude excercebat, hominem ſine intellectu, absque loquela, & veluti apoplecticum, & ſemimortuum invenit. Abraſis crinibus, & dilatato vulnere cum Elevatoriis aliisque inſtrumentis neceſſariis deſtitutus eſſet, terebellum, quo doliarii utuntur, ſibi adferendum jubet, cujus aciem cum in rimam ipſam Cranii infixiſſet, maxima cum dexteritate, non ſolum impreſſum Cranium in priſtinum locum repoſuit, verum & fragmenta nonnulla extraxit: operatio adeo feliciter ſucceſſit, ut ſymptomata protinus remiſerint, & æger tandem convaluerit: imo & per multos annos ſupervixerit, non ſine admiratione omnium. Hujus curationis & ſanationis ego quoque teſtis ſum ocularis.

Hæc

Fig. 14.5 (continued)

CENTURIA II. 83

Obs. 5.

Terebellum.

Officiū fidelis Chirurgi. Hæc propterea adscribo, ne fidelis ac diligens Chirurgus ægrum periclitantem, propter penuriam instrumentorum derelinquat, aut operationem usque dum instrumenta fabricata fuerint, maximo cum damno ægri protrahat, quin potius, quod commode substitui possit, id minime negligat.

Admonitio ad Chirurgos. Cæterum monitos velim esse Chirurgos, ut prospiciant, ne operationes & curationes, quæ in capite occurrunt, inprimis ubi meninges, & cerebrum detectum est, in loco frigido fiant: frigidum enim cum sit inimicum cerebro, nervis &c. ut Hippocrates lib. 5. Aph. 18. atque experientia ipsa docet, non potest non gravissima & persæpe mortalia symptomata excitare. Quapropter in vulneribus capitis præsertim magnis & periculosis, sartaginem prunis impletam vulneri, interim dum id curo, per ministrum aut aliquem ex adstantibus admovere jubeo.

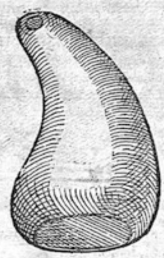
OBSERVATIO V.

Puerorum depressum cranium, quomodo elevandum.

PUerorum Calvarias ex casu deprimi posse, nullis supervenientibus symptomatis, (nisi forsan in ipso casu vomitus cibi indigesti) aliquoties observavi. Cum enim eorum cranium adhuc molle ac tenerum sit, facile absque fractura deprimitur atque introcedit, quemadmodum argenteis & stanneis vasis ex solidorum corporum collisione accidere videmus. Hinc fit, quum dura mater, membrana alioquin exquisitissimo sensu prædita, à fragmentis non pungatur, ne sæviora symptomata sequantur. Interim tamen hujusmodi impressiones cranii, etsi in principio non adeo magni momenti esse videantur, gravioraque symptomata non inferant, spernendas tamen minime esse, omnes in arte versati intelligunt: Hujusmodi enim impressiones cerebri motum impediunt, & quo minus spiritus in cerebro elaborari possint, obstant. Hinc ingenium stupidum oboritur, caputque catarrhis obnoxium redditur. *Obs. 5. Primus modus elevationis Cranii.*

Porro in pueris sæpissime hujusmodi depressiones Cranii, abrasis crinibus, & apposita cucurbita, naribusque & ore clausis, quemadmodum Ambrosius Paræus Chirurgus æterna laude dignissimus lib. 10. cap. 5. recte docuit, in naturalem situm reposui.

Vel instrumentum sequens corneum & cavum loco impresso admoveatur, quod ex superiori sua parte à viro quodam robusto, interim dum os, & nares infantis clauduntur, sugatur. *Secundus modus.*



Aut Emplastrum aliquod tenaciter adhærescens, veluti ex pice, resina, colophonia, & gummi Elemi, in medio ossis depressi applicetur, Vel quod tenacius adhæret. *Tertius modus.*

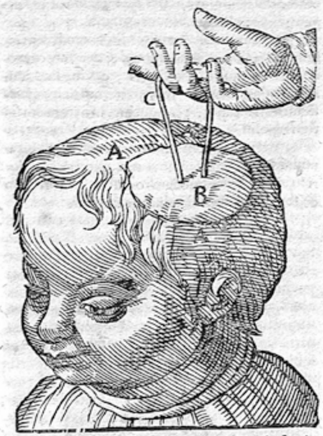
℞. Farinæ tritici ℥j.
Ichthyocollæ dissolutæ in aqua
Betonicæ & salviæ ʒ.ſ.
Pulv. masticis,
Thuris
Farinæ volatilis
Sanguinis drac. gypsi an. j.ſ.
Misce, coquantur in aqua betonicæ & salviæ ad justam consistentiam, applicetur calide. *Emplastri*

QUamprimum undiq; agglutinatum & exsiccatum fuerit emplastrum hoc, vi aufferatur, sic enim attracta cute & pericranio, craniū depressum simul elevabitur. Id si prima vice minus successerit, ab opere tamen minime desistendum, sed denuo novum emplastrum applicandum, & ut antea, vi aufferendum. Ut autem eò tenacius adhærere possit, capilli non omnino sunt abradendi. Hinc si dolor aliquis oritur, locus inungendus est oleo rosaceo, aut myrthino, & de vitellis ovorum Emplastrum autem hoc rotūdum, aut ejus figuræ, cujus est depressio cranii, esse convenit: Neque ejus sit magnitudinis, ut totam impressionem cranii, sed tantummodo tertiam circiter partem, cooperiat. Sic enim in ablatione minor erit dolor, & facilius impressum cranium elevabitur. Habeat præterea Emplastrum hoc in medio funiculum, quo à Chirurgo apprehendi possit, ut sequens denotat figura.

A. A. A. Cir-

Fig. 14.5 (continued)

Obſ. 5.



A.A.A. Circumferentiam depreſſionis ſive introceſſionis cranii, exhibet.

B. Emplaſtrum in medio hujus depreſſionis appoſitum, demonſtrat.

C. Funiculus eſt.

Interim autem, dum Chirurgus Emplaſtrum aufert, os & nares infantis, ut antea quoq; monuimus, claudendæ ſunt. Sic inflato cerebro propter retentionem in ipſo ſpirituum, cranium impreſſum facilius in ſitum naturalem relevabitur.

Verùm ſi his remediis, & manuali operatione cranium non relevetur, decuſſatim cutis incidenda, & denudato cranio, à pericranio, ſequenti elevatorio, aut meo, quod antea depinxi, cranium relevandum eſt. Vulnus deinde relictum, aliorum capitis vulnerum more, curari debet.

Admonitio. Hîc monitos velim Chirurgos, ne in perforatione cranii, diploidem, ſi fieri poteſt, tranſgrediantur: ſecundi enim tabulati, quod non adeò craſſum, ſed valdè friabile, perforatio, aſperitatem in cranio relinquit, quæ poſtea cerebrum pungendo, dolorem, aliaq́; ſymptomata, excitat.

OBSERVATIO VI.

Obſ. 6. & 7.

Ex perforatione Cranii neglecta, mors ſequuta.

NObilis quidam ex familia EWIGIORUM Waldenæ prope Hildenam, in conflictu quodam in bregma percuſſus, in terram proſtratus fuit, & cibum indigeſtum evomuit. Curatio ſtatim duobus Barbitonſoribus commiſſa. Ego quartâ die poſt, unà cum clariſs. viro D. JOANN. SLOTANO, apud Colonienſes Doctore Medico celeberrimo vocatus, ægrum febricitantem cum cranii fractura, offendimus. Vulnus verò contuſum & parvum erat: aderant quoque vigiliæ, inquietudines, dolores, & capitis gravitas. Ex quibus nobis facilè colligere licuit, pus cranio ſubeſſe. Quapropter ſuaſimus, ut dilatato vulnere, terebello, ſive ut vocant trepano, cranium perforetur, idq́; niſi maturè fieret, ægrum in maximo vitæ diſcrimine verſari, prædiximus. Barbitonſores contrà mira ſe præſtituros, gloriabantur, & perforationem cranii, tanquam remedium eis incognitum & crudele, arroganter reſpuerunt, & apud adſtantem turbam ſuſpectum & odioſum reddiderunt. Nos itaque cùm ejuſmodi collegas nobis adjunctos habere, nec honeſtum, nec ægro utile eſſe videremus, febrim item de hora in horam ingraveſcere, cumq́; barbitonſores, univerſalia ut adhiberentur, concedere nollent, altera die diſceſſimus, & manum deinceps admovere recuſavimus, ne propter ignorantiam barbitonſorum noſtra ſimul fama atque æſtimatio periclitaretur. Poſt noſtri abitum, & quidem ante undecimum diem morbi, auctâ febri & deliriis, tandem loquelam quoque æger amiſit, & ex oppoſita vulneris parte paralyſi correptus, ante decimam quartam diem, finem vitæ ſuæ impoſuit.

OBSERVATIO VII.

Suturæ cranii ex vehementisſimo dolore capitis disjunctæ.

THEODORUS *auff den Houlen* Hildenæ, annum ætatis quadrageſimum circiter agens, robuſtiſſimo corporis habitu, & qui vix unquam morbo detentus, incidit in febrim continuam circa dies caniculares, anno 1592. In principio morbo neglecto, ſymptomata adeò ingraveſcebant, præcipuè verò dolor, vigilia & phreneſis, ut à tertio die, ad octavum & nonum uſque, nullum ſomnum capeſſere potuerit. Id autem nobis notatu dignum in ipſo obſervare licuit, nimirum quòd circa ſextum & ſeptimum diem ſutura ſagittalis & coronalis, adeò à ſe invicem disjuncta deprehendebatur, ut adſtantes non modo tactu, verùm etiam ſyſtole & diaſtole cerebri, ſuturis digito impoſito, eodem prorſus modo, ut in pueris, antequam eorum cranium penitùs obduruerit, facilè percipere poſſent. Septimo verò die ſupervenit ſudor criticus, adeò copioſus, ut contoriâ ſubuculâ aqua, ac ſi croco tincta fuiſſet ubertim exſtillaret. Hujus ſudoris beneficio reſtitutus & liberatus fuit, ſuturæ quoque paulò poſt ſenſim coaluerunt, adeò ut ad 1610. ſupervixerit. Ejusdem

Fig. 14.5 (continued)

ilar to the *'tirefond'*, to screw it in the bone, taking care not to puncture the brain.

Fabry's contributions to general surgery were so important that, among German surgeons, he is compared to what Paré meant for French surgeons. For this reason, he is considered the father of German surgery.

Johannes Scultetus (1595–1645) (Schultheiss Latinised to Scultetus) was a remarkable surgeon born in Ulm (Germany), remembered nowadays for his abdominal binder. His life has been reviewed recently by Scultetus and collaborators [9]. He was a servant in Vienna when he was patron by the Professor of Anatomy of Padua Adriaan van de Spieghel. In Padua he met Fabricius d'Aquapendente and completed his academic and medical career. At the end, he became the city physician of Ulm. He wrote in Latin a textbook of surgery, the *'Armamentarium Chirurgicum'*, published by his nephew Johannes Scultetus the Younger in 1655, just 10 years after his death [10]. The book was very soon re-edited several times and translated to different live languages, in 1666 to German. The book is organised in two parts. The first part deals with the surgical instruments and surgical techniques and includes 43 plates (*'tabulae'*), about one-fourth of them dedicated to head injuries and their surgical treatment. The second part describes 100 personal surgical case reports (*'Observationes'*), again with a number of them describing head injuries. His interest in the head injuries is probably due to the fact that he was involved as surgeon in the Thirty Years' War.

The precise and obsessive detail in his description techniques allowed barber surgeons, students and surgeons to easily follow the steps of the different surgical procedures. In the same way, the precise detail in the illustrations of the surgical instruments helped blacksmiths to manufacture the tools demanded by the surgeons for their own use.

However, Scultetus was very critical with the work done by the barber surgeons. In the modern paper by Scultetus [9] we can find the description of a case of head injury treated wrongly by a barber surgeon, and later operated on by himself successfully: 'He was treated by a local barber surgeon in a simple way as any other wound would have been treated an was considered cured in 7 days. Eight days later, the man started to complain about increased swelling over the injured part of the head as well as headaches. The wound was explored by myself. After dilatation of the wound a fracture of the skull was noticed and a trephination was performed. It was found that the puncture of the skull included both laminae and upon perforation with the modiolus on the twelfth day, material that accumulated over the dura mater was removed … On the thirteenth day headache was gone. On the fourteenth day the inflammation was go … On the fortieth day the wound was closed'.

In the *'Armamentarium Chirurgicum'* surgical instruments are represented in a total of 11 plates (*'tabulae'*), plates II to VI related to cranial surgery (Fig. 14.6). The explanation of each of the figures of every plate is located in separate pages and grouped for each of the plates.

In plate II (*'Tabula Secunda. De Spatha Celsi, cuatro rasorio, modiolroum mare, fæminis, & vertibulo; instrumento lenticulari, vecte debilissimo, membranæ custode, instrumento decussorio: quibus Chirurgo opus est adcurandas fracturas Cranii'*) are illustrated eight different instruments for cranial trepanation. Figure III is the *'Modiolus mas'* (male) described as follows: 'It is a hollow instrument with smooth walls with four wings and serrated edge endowed in the center of a stylet that, once denudated the skull of the soft parts, is fixed to perforate by rotation. Being the instrument steady, the maneuver avoids pain by attrition of the soft parts of the wound'. Figures IV and V show two *'Modioli fæminæ'* (female) explained as follows: 'They are the same size as the previous male, and I think they are equal to them except that they lack the stylet, and this is the reason for their name. Before this feminine modiolus can be used it must enjoy the benefits of a skull with some trace of the masculine impression, since the females need a firmer base. At least three modioli are required, at least two females and one male, so that from time to time they can be changed and submerged in cold water or rose oil, to remove the bone dust that fills the operative field and for the heat of rotation that inflames the skull membranes. The invention of modiolus wings prevents the instrument from sinking into the membranes of the brain'. Figure VI displays a *'Vertibulum'*, defined as 'A handle that has a hole for insert the end of the modioli wrapped in cotton, that are extracted whenever a change is necessary. For this reason, *"modiolus"* and *"vertibulum"* make up the *"Trypanis"* (trepan), with which the skull can be easily pierced quickly and easily'. Figure VII shows a

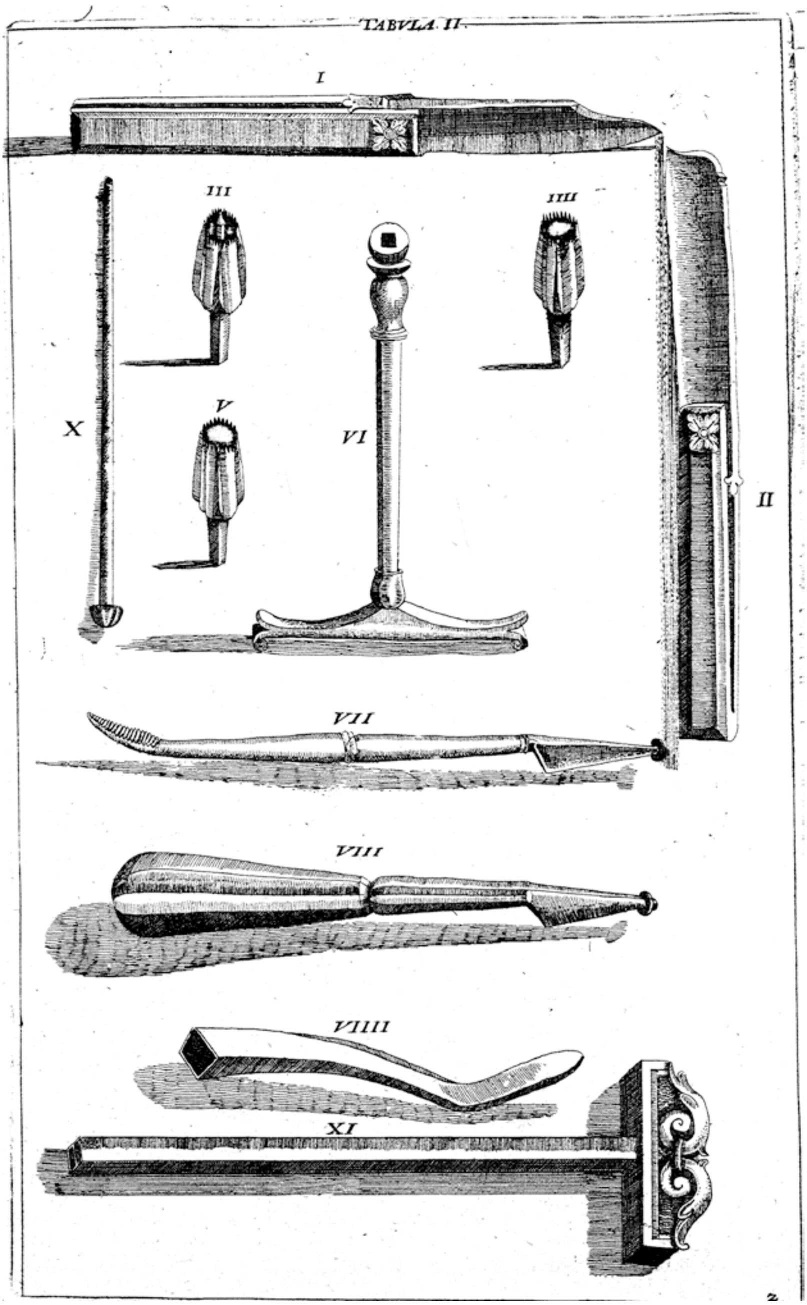


Fig. 14.6 Instruments related to trepanation by Johannes Scultetus (Scultetus J. Armamentarium Chirurgicum. Ulme Suevorum; Balthasari, 1655)

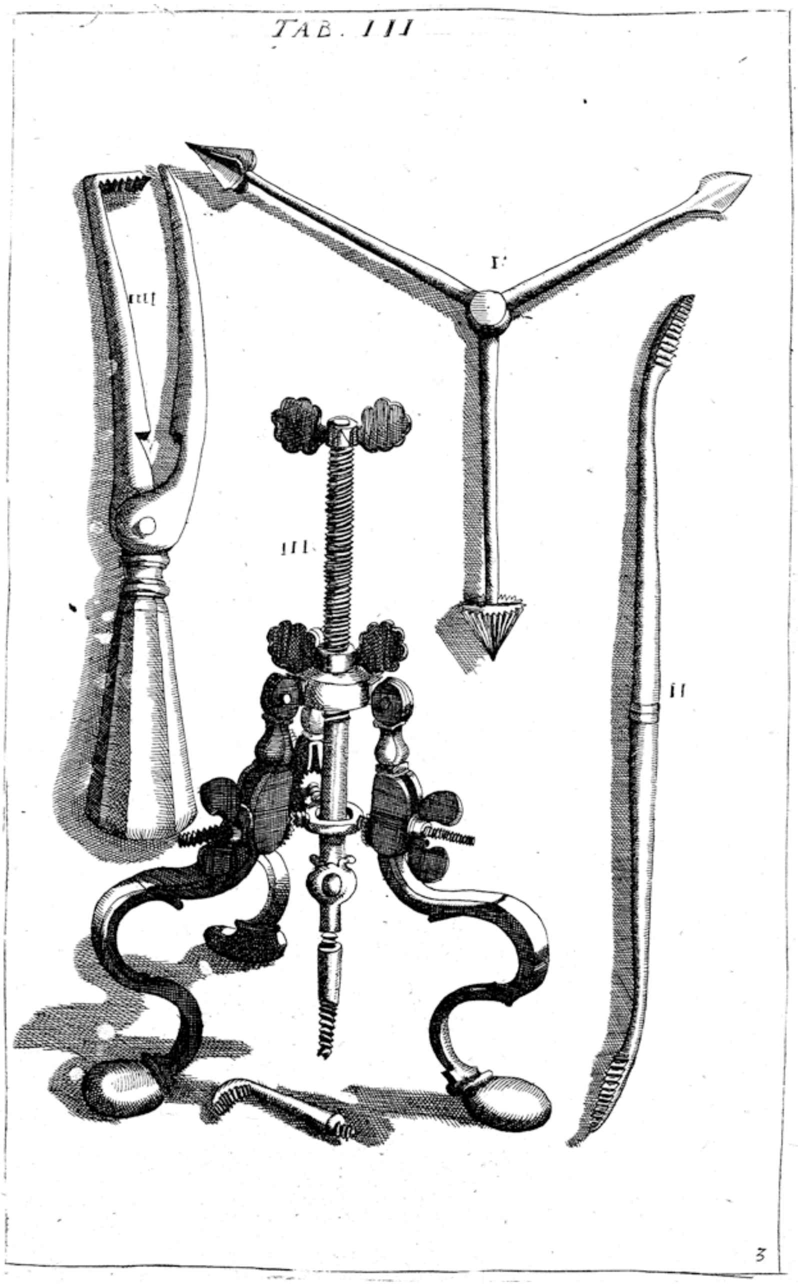


Fig. 14.6 (continued)

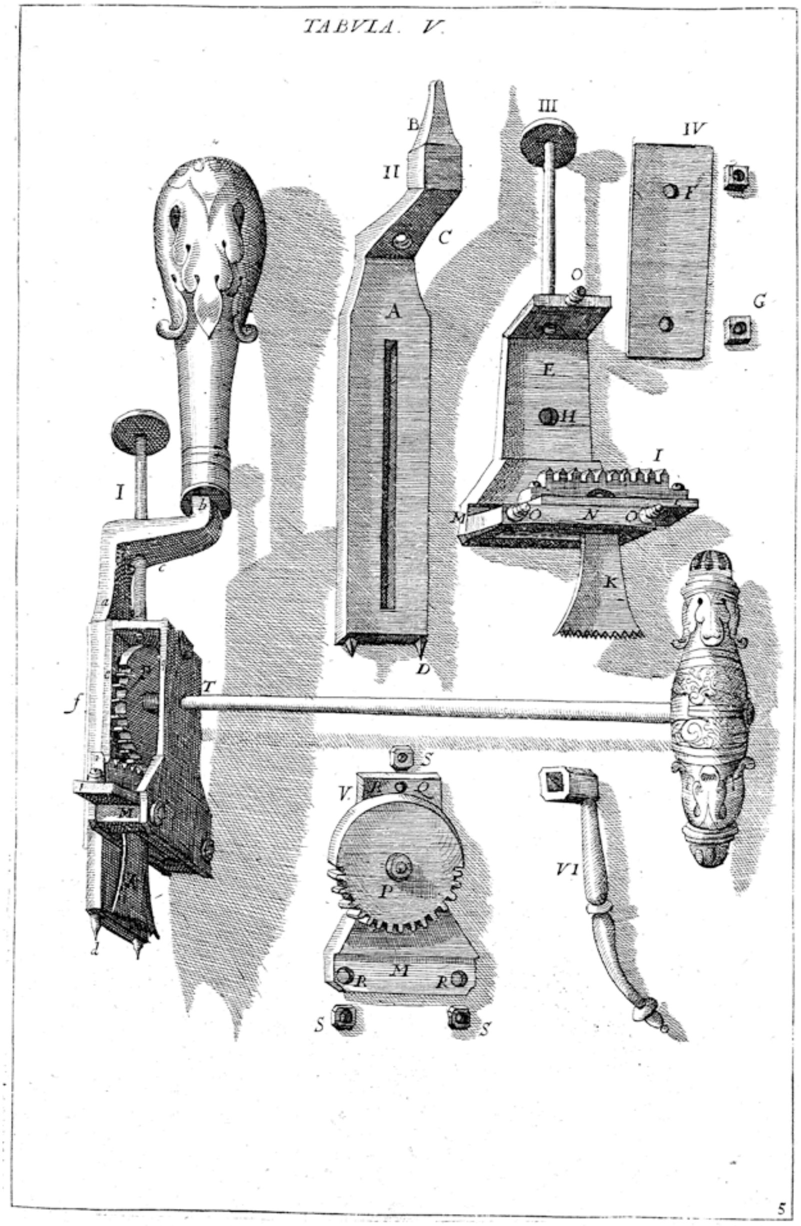


Fig. 14.6 (continued)

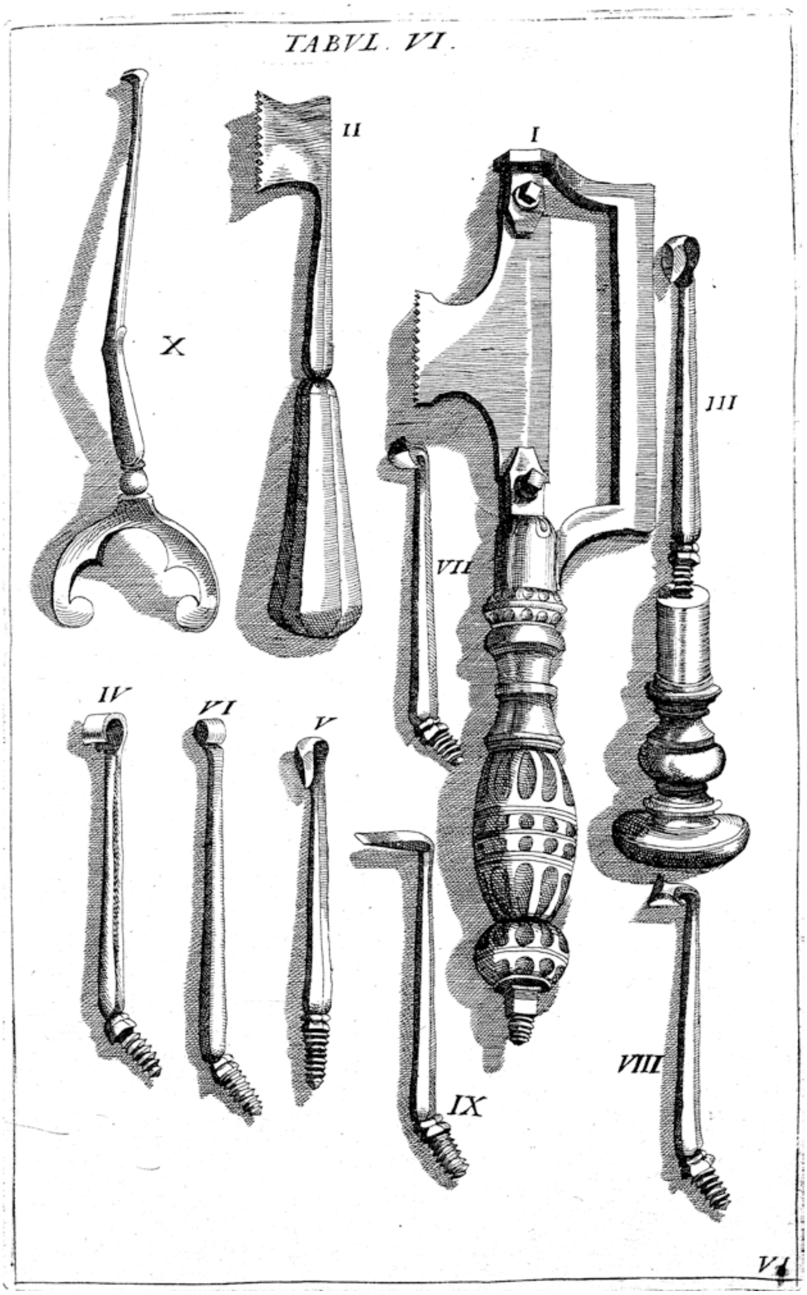


Fig. 14.6 (continued)

'Lenticular' described as follows: 'The instrument consists of a dissector on one end and a lenticular instrument on the other end. It is used at the end of the skull piercing to remove bone spicules and elevate bone fragments. When the lentil loses the smoothness the covers of the brain can be offended with the continuous movement of these pieces'. Figure VIII is a *'Lenticular'*, that is, a lenticular instrument. Figure IX shows a *'Membranae custos'*, described as an 'Iron sheet to separate the skull from the brain membrane and which in Greek is called *"meningophylax"*'.

Figure X depicts the *'Instrumentun depressorium'*, a 'depressor of the dura once pierced in the skull with the modiolus to extract material and purulent collections'. Figure XI is the *'Malleus plumbeus'*, or lead hammer.

Plate III (*'Tabula Tertia. Terebra triformi, vecte validiore, Instrument triploide & elevarorio Paræi, quibus cranii puncturæ abolentur, ejusdemque depressions eriguntur'* gathers instruments to partially pierce the skull in order to raise fractures. Figure I is the *'Terebra triformis'*, a 'Perforating instrument made of iron, which consists of three legs and which are used to pierce the skull, but which does not penetrate the two tables. This instrument can be replaced by the *"terebella"*, with which the cranial perforations were made before the introduction of this instrument'. Figure II is an elevator of bone fragments. Figure III depicts a *'Triploides'*, described in the text as 'An instrument designed to elevate the bone fragments so sunken that they cannot be lifted with the elevators. To do this, you have to drill the bone, but avoid crossing the two laminae or puncturing the dura mater'. Finally, Fig. IV is a bone forceps.

Plate V *('Tabula V. De Serrula versatili, qua duorum foraminum interstitum exciditur')* is very interesting. Here is represented in Fig. I the *'serrula versatilis', the* first horizontal cutting saw described in the world and which was designed to cut the bone between the holes made in the skull with the *'modiulus'*, in order to expand the cranial opening. The instrument is described by Scultetus as follows: 'It is an instrument equipped with a handle that moves a turning drum with a serrated saw. It has two fixing teeth. It is especially useful for cutting the bone between every two of the skull holes made with the modiolus'. The assembled and exploded saw is presented and all parts of the instrument are described with letters.

Finally, plate VI *('Tabula Sexta. Serrulis rectis, & variis scalpis, quibus cranium vel cariosum vel fissum* abraditur'*)* collects two straight cranial saws and a variety of skull scrapers useful for when it meets with caries, that is, inflammatory or tumour pathology. The scrapers are interchangeable to be used in a handle also illustrated (Figs. I and II. *'Serrulae rectae'*; Figs. III–X. *'Scalprorum'*).

There is a short work authored by Johannes Scultetus, published in 1692 and edited by his heirs, entitled *'Actuarium ad armamentarium chirurgicum'* [11], that has only 30 pages and includes 10 additional plates to the book *'Armamentarium Chirurgicum'* by the same author published in 1655. The book contains some figures related to cranial trepanation and the explanation is found in the text. In *Tabula I* are drawn two instruments for trepanation: *'modiolus femina in later pertusus'* (Fig. i), which has a perforated side, through which the sawdust of the bone can be evacuated; meanwhile the male modiolus does not require this hole, and the *'Scalprum incisorum'* (Fig. vii) is used with the hammer to eliminate sharp edges of bone. The text says that modern authors are more cautious and prefer to use tweezers instead of chisel and hammer. In *'Tabula VII' ('De ratione duram matrem deprimendi, calvariam depressam elevandi, foraminum que duorum interstitium ferrulis excidendi, ossicula cranii separandi, vulneque capitis curandi'*), the author describes different surgical techniques applied on the head of three different patients. It must be highlighted that all scalp openings are always in cross. In Fig. I Scultetus shows how the dura mater depressor instrument works. When applied through a trepan, it allows the collection of material under the skull, either spontaneously or favoured by retaining the expiration or covering the nose. Figure ii shows an injured skull, carefully exposed by the surgeon and without visible fracture, because as Scultetus points out sometimes the external table is intact and the internal table is fissured. In figure iii the author shows how to elevate a cranial depression with the *'triploid terebram'*. The instrument drills in the centre of the depression by turning the upper wing, taking care not to pierce the two tables of bone and puncture the dura mater. When the tip is firmly attached to the skull, the surgeon lifts the bone by rotating the lower pommel, until the surface of the skull is even. With the skull elevated, the tip of the *'triploid'* is removed and then the whole instrument is disconnected. Figures iv, v and vi show different cranial lesions. Figure vii shows 'the resection of bone fragments to the old way, in the way that modern surgeons have rightly rejected the use of the chisel and the hammer, which can move to the brain'. Finally, figure viii shows the cranial wound with the injured skull, which is called *'dedolationem'*.

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15 Trepanation out of Europe: New World and Japan

Outside Europe the trepanation spreads after the sixteenth century thanks to the European colonial expansion in America and Asia. With the discovery of the New World by Spain and the maritime expeditions of Portugal to the Far East in the sixteenth century looking for the species begins the era of colonialism of European nations throughout the world. Later, other European powers joined, such as Great Britain, Holland or France. Finally, Germany or the United States will do it. In this way, the customs, religion, culture, technology, administrative and political organisation, rules, laws and European standards spread throughout the world. The colonial powers carry, among other things, European medicine and surgery and, consequently, the techniques, instruments and indications of cranial surgery and trepanation. This activity was closely linked to the capabilities and organisation of naval surgery, since ships were the means of transport but also authentic floating sanctuaries of the medical heritage and the surgical knowledge thanks to the naval surgeons belonging to the commercial companies or the navies, and also the chest of the necessary technology, since it was shipped in the port of origin without possibility of improvements along the long maritime journeys.

15.1 Trepanation in the New World

As we have mentioned in the previous chapters, there are no references in the Spanish chronicles of the conquest about the trepanations carried out by the American indigenous peoples. Therefore, it is not known when they stopped carrying them out until the Spanish acculturation was completed. There was probably a sudden crisis due to the drastic reduction of the native population and the rapid collapse of the indigenous political, social and cultural structures. However, we must not forget that both cultures and the medicine of both cultures had to coexist for some time compulsorily.

The first documented cranial surgery in the New World was carried out by a Spanish surgeon called Pedro Arias de Benavides (1521–1570?) in Mexico City in 1561. Arias de Benavides was born in Zamora and he was probably trained in surgery in Salamanca. He arrived in Mexico after staying in the Canary Islands and in several Caribbean towns [1]. The patient treated by Arias de Benavides was a 13-year-old boy with a wound caused by a firearm (a culverin). He showed an open fracture with injury of the dura mater, exposing the brain. Arias

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de Benavides strictly treated the patient according to the general principles accepted in that time, which were almost the same ones described by Hippocrates and the authors from the Middle Ages. The patient survived against all odds as this type of injuries normally involved a fatal prognosis. The treatment consisted of repeatedly washing and cleaning the wound and fragment removal. No references were made about any type of trepanation. The case was described by Arias de Benavides in his book *'Secretos de Chirurgia'*, which was published in Valladolid (Spain) in 1567.

The first medical text published in America that gathered the treatment technique of cranial wounds was *'Summa y recopilación de Chirurgia'*, written by Alonso López de Hinojosos and edited in Mexico in 1578. It strictly followed Albucasis' recommendations, i.e. those made in the Middle Ages. Some cranial interventions carried out in America were recorded later, particularly a skull bone fragment removal that was carried out by Pedro Gago de Vadillo in Peru in 1602. There is a later evidence of the trepanations carried out by P. Blandain, P. Bigot and J.B.F. Pelegrin in Caracas in 1736; by Narciso Esparragoza y Gallardo in Guatemala in 1789; and by Sebastián Barceló in Mexico in 1793.

We have not found any evidence about the original trepanations of British or other European colonies in North America. As an anecdote, we must point out that the first image of a physician using a trephine was probably a portrait of John Clarke (1609–1676) made in 1664 (Fig. 15.1).

Fig. 15.1 Portrait of John Clark, painted c.1664 by an unknown artist (OnView: Digital Collections & Exhibits, accessed March 31, 2019, https://collections.countway.harvard.edu/onview/items/show/6422)

He was holding a trephine with a T-handle that was typical of English-speaking countries. He was applying it to a dried skull. On the background of the image it is possible to observe a skull saw with double edge. John Clarke was born in England but he moved to New England, where he practised medicine. However, his most important job was as a baptist minister and politician.

15.2 Trepanation in Far East: Japan

European medicine, along with trepanation, also spread to areas that were now subjected to occupation and colonisation by the European powers in Asia thanks to trading companies. An example of this was Japan, where Chinese traditional medicine was practised and there was a huge opposition to Western medicine [2–4]. Francisco de Javier (1506–1552) was a Spanish Jesuit monk who visited Japan in 1549. He was authorised to carry out a mission to attend sick people. The Portuguese Jesuit Luis de Almeida (1525–1583) founded a hospital later, in 1557. The surgical interventions were carried out in Japan by Spanish and Portuguese surgeons following the European procedures. As this care work was accompanied by an aggressive evangelisation, missionaries were tormented and executed by the political local authorities, and the Europeans were expelled in 1596. Later, a Dutch merchant ship arrived on the islands in 1600. Therefore, they established purely economic relationships with the Netherlands from 1608 on that allowed trading activities at the port of Nagasaki. Physicians and surgeons of the Dutch vessels served as distributors of European medicine from then on. The Japanese physicians were eager to learn from them, particularly the techniques of surgical interventions. Almost only the Dutch surgeons from the vessels of the Vereenigde Oost-Indische Compagnie had dealings with the Japanese physicians during the Edo period, which covered from 1603 to 1868 [5]. They taught them the so-called red hair style surgery (*'Koumou-Ryu-Geka'*). The import embargo of Dutch books ended in 1720. Later on, Japanese authors started publishing translations of the Western medicine books. The imperial Japanese Government decided to follow German medicine in 1869. The influence of such medicine persisted until the end of the World War II.

The first texts on Western medicine that were written in Japanese were more or less free translations of European books that were in turn translated from their original languages into Dutch and arrived to Japan in the Dutch vessels. The most important one in historical terms was the Dutch translation of *'De Chirurgie'* written by Ambroise Paré (1510–1590). It was translated in turn into Japanese by Eikyū Narabayashi (1648–1711) in 1706 under the title *'Geka sōden'* and by other translators subsequently.

Mitsuaki Irako translated also to Japanese the book *'De chirurgie, ende opera van alle de wercken'*, which is a Dutch translation done in 1649 [6]. The book has some illustrations similar to those included in the Paré's book, some of them devoted to trepanation. The book was printed with woodcut technique. The book reproduces cranial surgery techniques and bandages, including trepanation and its instruments. The drawings are very rudimentary. Irako's book was published in two volumes in Japanese language, being in turn a copy of a previous version written in Chinese style.

In the book there are some plates related with the cranial surgery (Fig. 15.2). In the first and second plates several cutting and scraping instruments are represented, with a multipurpose handle where they can be attached for handling. Then there is a plate with a patient with a shaved head and in which there are several marks. The main cranial sutures have been drawn schematically. On the next plate a cylindrical trephine crown with a cutting surface and a central pyramid and mounted on a T-handle is recognised. Another three-armed instrument resembles the *'tirefonds'*, but with two legs ending in punches and the third in a slotted perforator. A double lifting and/or scraping instrument as well as a bandage are also represented. In the upper right part there is an instrument that resembles the lenticular knife. In the two following pages, patients are represented on which the trephine and the triploid are applied and, finally, in the last one a patient is drawn with the bandage applied on his head.

Another European book that was translated and had a great impact was the second Dutch edition of the book *'Chirurgie'* by Lorenz Heister (1683–1758). It was published by several Japanese authors in 30 volumes throughout many years. These texts included illustrations of surgical interventions and trepanations. Those made by Kōgyū Yoshio (1724–1800) were particularly interesting. Yoshio was a Japanese interpreter from Nagasaki, who learned Dutch and became a surgeon. As other Japanese physicians he translated into Japanese several European books and parts of them, written in Dutch and which in turn were translations of the originals in Latin or other languages. He was interested in the Dutch version of the book *'De chirurgie'* by Ambroise Paré and apparently copied some of Paré's drawings to illustrate some of his writings. One first sheet represents several instruments related to trepanation and one patient with the bandage applied and the second the use and application of a *'triploid'* perforator in a patient, and a second patient with a cross incision in his head (Fig. 15.3).

However, there is no written evidence in Japan of trepanations or cranial surgery throughout this long period of time. As medicine was very advanced in Japan during that time and as trepanation was a complex surgical intervention it

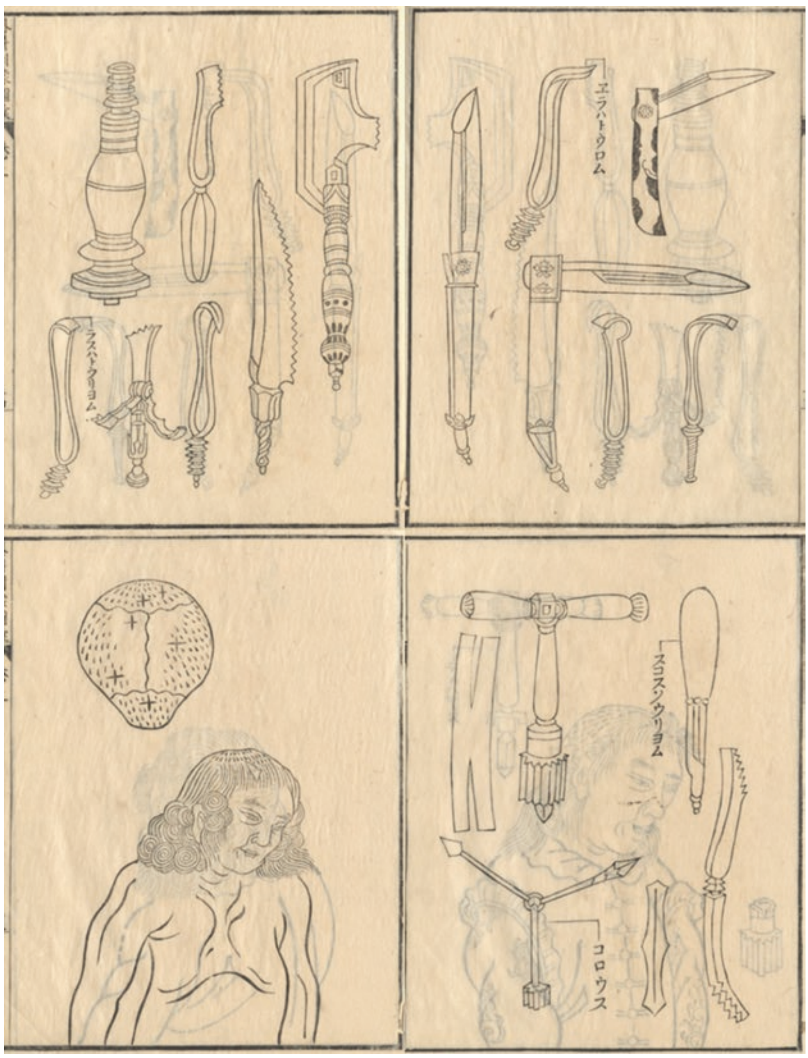

Fig. 15.2 Instruments and techniques of trepanation by Mitsuaki Irako (Paré A, Irako M (éd.). Geka kinmō zui/ Rō Mitsuaki Kōhaku kantei; Den Takanobu Shūan, Ka Norimitsu Yūji dōkō. Kyoto: Hayashi Sōbē hakkō, Meiwa 6, 1769)

Fig. 15.2 (continued)

would be strange that they had not left any written evidence in case they had carried it out. There are no reliable archaeological remains of trepanations carried out during the Edo period either, or from previous periods. Some skulls with drills have been found but they do not show any palaeontological sign of survival. As we have mentioned, trepanation was a technique described in the texts that were translated into Japanese. For this reason, some authors suggest that they were postmortem drills made for training. Other authors think that they were war wounds as it was a violent period and there was a wide range of weapons used in the battles.

The first documented neurosurgical case in Japan took place during Seinan Civil War in Kyusyu in 1877. A physician from the army, called Susumu Sato, operated a 34-year-old soldier who suffered an injury on the head caused by a bullet. The surgical procedure was a trepanation. He removed the depressed bone piece and the bullet from inside the epidural space and drained an abscess. The symptoms improved but the patient died 10 days after due to a pneumonia. A successful cranial surgery was carried out by Julius Scriba, a German surgery lecturer invited by the University of Tokyo, in 1892 to treat a depressed fracture.

Fig. 15.3 Instruments and techniques of trepanation in Japanese literature around 1790

Fig. 15.3 (continued)

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16 Trepanation During the Eighteenth Century: To Trepan or not to Trepan

Terrier and Péraire called the eighteenth century the ‘trepan century’ due to the interest on trepanation in Europe, both in France and Great Britain, but particularly in the former [1]. In effect, the surgeons increasingly recommended trepanation during the first decades of the century, even for those cases of cranial trauma without a wound or without obvious symptoms of brain compression. Some authors even recommended a prophylactic trepanation to prevent the complications of head trauma and wounds. This trepanation obsession caused quite a stir due to the recommendations made by Percivall Pott (1713–1788) supporting the trepanation. During this period of time, French surgeons also started showing their preference for the brace handle systems contrary to the English surgeons, who preferred the borehole handle and the saws. Surgeons achieved to completely break the taboo of opening the dura mater in trauma injuries during these years. This procedure was already recommended by surgeons such as Lorenz Heister (1683–1758). Little by little and after observing particular cases they proved and accepted the feasibility of trepanning on sutures, the frontal bone, dural sinuses, temporal fossa or temple and suboccipital area. Hence, the territory limits of trepanation set by Hippocrates that were respected over centuries were finally overcome.

The trepanation was a task for surgeons in the eighteenth century. It was only carried out by physicians on an exceptional basis. Physicians recommended the surgical treatment but rarely followed up the patients who underwent the surgery. English surgeons started being trained in their early adolescence as apprentices at the beginning of the eighteenth century. They accompanied and assisted surgeons at the hospitals. They took an exam before the Court of Examiners of the Company of Barber Surgeons after several years of training. Then they had to demonstrate their qualification for practising surgery. However, the Company of Surgeons separated from the Company of Barbers in 1745. The surgeon carried out his duties then as an Assistant Surgeon at the hospitals, in the army, in the navy or in private practices.

As an anecdote, the first trepanations carried out by veterinarians on domestic animals were described in the eighteenth century. They were initially carried out to treat infections, polyps, tumours or foreign bodies in the frontal sinuses, whereas the maxillary sinus was trepanned in horses to treat dental diseases. Cranial trepanation on animals was exceptional but it was indicated for treating brain hydatid cysts in sheep and beef cattle. The clinical suspicion was instability and falls and the diagnosis was of a clinical nature. After trepanning, the brain was punched to drain the liquid of the cyst and the membranes were later removed.

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16.1 'State of the Art' of Trepanation and Trephine at the Beginning of the Eighteenth Century: *'A Remarkable Case in Surgery'* by Turner

Daniel Turner (1667–1741) published a particularly detailed clinical case in 1709 in the monograph *'A remarkable case in surgery: wherein an account is given of an uncommon fracture and depression of the skull, in a child about six years old; Accompanied with a large abscess or aposteme upon the brain. With other practical observations and useful reflections there upon the brain. Also, an exact draught of the case, annex'd. And for the entertainment of the senior, but instruction of the junior practitioners. Communicated'* [2]. It allows to illustrate the *'state of the art'* of the trepanation technique at the beginning of the eighteenth century. The patient was a 6-year-old boy who was hit on the right side of the head on the 24th of February and showed a small wound. The wound was manually examined by Turner, who found a depressed fracture. The barber initially shaved the skull and performed a bloodletting. A circular cut was made on the pericranium the following day to completely expose the fracture. The injury had a circular shape and four depressed fragments. As there was no space between the fragments to lift them with the lifter the trepanation was required. Turner considered that the *'Terebra'* (punch) would be inadequate and dangerous for the *'Dura Mater'*. On the other hand, the *'Trepan'* (trephine crown) was also dangerous for such a young child because the *'Membrane'* (dura mater) was very adhered to the bone in children. Finally, Turner decided to use the *'Trepan'*. When the intervention started there was an arterial haemorrhage that was stopped but forced to postpone the trepanation. The wound was exposed again on the 27th of February. The fracture could be easily noticed and the sutures were identified. Turner commented that the best place for trepanning and using the lifter was the upper part of the fracture. As there was not enough space for trepanning an additional portion of the pericranium was resected. Finally, the trepanation was carried out on the 28th. Turner described it as follows: *'I gently turn'd the Instrument, now and then taking it up to clean, 'till I had got to the Diploe: when lifting it out again, brushing off the Saw dust, and laying the Pinafide, I proceeded to work farther, examining with my Probe betwixt whiles, where I was got thro', and bearing down upon those parts where I found I was. In few minutes the work was dispatch'd and being willing to have it out as clear as I could, without having occasion to hiver off any part that might remain undivided by the Saw'*. The trepanation hole was satisfactory as *'The Warden was pleas'd however with the operation, the edges of the bone were so exactly smooth and even, that we needed no Lenticular to come after, for to polish the work'*. Once the trepanation was made he lifted the fragments of the fracture as follows: *'And now we immediately set about the lifting up the deprest bones; in order to which pasting carefully my Elevator thro' the perforation'*, and then *'I began to lift having placed the end of the said Instrument under the center of the largest and most likely of them when bearing up with considerable force'*. After removing four fragments of bone they could saw the dura mater pulsing. It was washed with a sponge soaked in warm claret wine and then they applied the dressings. They repeatedly washed the wounds and changed the dressings, waiting for cicatrisation by secondary intention.

No anaesthetics or sedatives were applied any time. The patient was held by an assistant. All the treatment was carried out at the patient's house. The surgeon was assisted by another surgeon. Turner himself felt pity for the child and admitted how brave he was by saying: *'Thus did this little Hero, of truly manly courage, who had struggled under, and got thro' so many difficulties, … at last decease, after fourscore and four days'*.

Turner included several pages at the end of the description of the case to make *'An advertisement to the common reader, for rectifying as common error'* concerning the belief that osseous defects caused by trepanation were covered with gold or silver sheets that were fixed to the hole. After a long explanation he concluded that it was not necessary. He pointed out that new tissue that covered the brain and even filled (*'by the help of the Art'*) the margins of the skull was formed a few days after the trepanation. It hardened, forming what the surgeons called *'callus'*, which became as hard as any other part of the skull. This erroneous belief is reflected in novels and pseudoscientific writings throughout history and, according to what was written by Turner, was already controversial at that time.

16.2 Two Confronted Points of View About Cranial Trepanation

After some decades of enthusiasm about the trepanation, two opposed points of view concerning the treatment by trepanation of cranial fractures started to appear at the middle of the eighteenth century. Percivall Pott (1713–1788), from Great Britain, was a firm supporter and leader of early trepanation in all cranial fractures, regardless of their type or clinical manifestations. On the contrary, the French surgeon Jean-Louis Petit (1674–1750) had a completely different point of view as he was more conservative. He admitted that trepanations involved many complications related to the technique itself and that many linear cranial fractures had a good prognosis without requiring to be trepanned. This more conservative attitude was based on the observations made by the French school. They noticed that different events happen after a cranial trauma, some of them would be primary, either structural (like the wound or the fracture) or functional (like the concussion) and later events would be secondary, such as the brain inflammation (cerebral oedema or congestion) or intracranial effusions (haematoma or infection). French authors also confirmed that there were two types of clinical symptoms with a different meaning: the initial concussion symptoms and the later symptoms of cerebral suffering. Therefore, there were a wide range of clinical situations in which a treatment by trepanation would be justified only on an exceptional basis. All these considerations made surgeons change the centre of attention from the scalp and skull to the brain. Thus, the role of trepanation in the treatment of fractures and cranial traumas was deeply reconsidered.

Pott's aggressive doctrine became popular in Great Britain and Petit's conservatory point of view was fervently followed in France. The surgeons from those countries and the rest of Europe and their colonies started taking sides. Surgical texts of that time identified these groups and even gathered lists of their followers in the different countries or geographical areas, dividing them into those for or against trepanation and the eclectic ones. It was such a radical discussion that it could be summed up in a single dilemma: 'whether to trepan or not'.

These radically opposed points of view concerning the application of trepanation on cranial fractures (which was the only indication of this treatment in that time) will be explained along with their most characteristic supporters. Among those people who were for trepanation we must highlight the French's Pierre Dionis and the English's Percivall Pott. As a representative figure of the abstaining point of view we have chosen the French' Pierre-Joseph Desault but his disciples, such as Xavier Bichat, later supported it. Some surgeons initially supported the trepanation but they strongly criticised it later, such as Jean-Louis Petit or Pierre-Joseph Desault himself. Finally, as an example of an eclectic point of view we have included the German Lorenz Heister and the Scottish Benjamin Bell.

Pierre Dionis (1643–1718) was a French author who published the work *'Cours d'opérations'* at the beginning of the century, in 1709 [3]. It can be considered as a proof of the initial interest (which became disproportionate) in trepanation. Dionis classified the skull fractures in three groups with a total amount of 12 subtypes of injuries. He recommended trepanning in all fractures, except for the *'tlasis'* or depressions with no apparent cause in children. He recommended making an exploratory incision the following day if there was no wound on the head to find the fracture, which could be directly observed, palpated with the finger or explored with a probe. Concerning the importance of the symptoms he had an aggressive point of view as he considered that trepanation was a preventive procedure against complications. For example, if a patient falls due to a loss of consciousness after a trauma he had to be trepanned. He criticised ancient surgeons for trepanning too late. However, he still observed many precautions concerning the areas of the skull to be trepanned. Also, he did not recommend the use of the exfoliating trepan. He included the description of many of his own clinical cases in support of his arguments and conclusions about the goodness of the trepanation. As an example, Dionis described the following astonishing case in his book: ‘A young woman who was about eleven or twelve years old fell down the stairs in 1705. She broke her parietal bone and part of her temporal bone. M. Maréchal trepanned her the following morning in two points. He also made a third burr hole due to his son and a fourth one in honour of my children, who were present. He made two other burr holes the following day and carried out up to twelve consecutive trepanations but she healed in the end. She was the daughter of M. Le Valfeur, who was staying at the Extraordinaire des Guerres in Versailles. This strange example proves that a person can bear multiple trepanations’.

In this surgical treatise by Dionis there are three figures related to cranial trepanation and the explanation of them appears interspersed in the text (Fig. 16.1). Figure XXX (‘*Pour les fractures du crane*’) includes the following instruments: Abscess lancet (A). Silver probe (B). Scissors (C). Straight scalpel (D). Myrtle leaf (E). Needle (F) and waxed thread (G). Linen compress (H). Brace trepan with perforator (I). ‘*Tirefond*’ normal (K) and small (L). Elevator ‘triploid’ (M). ‘Rugines’ (N, O, P, Q) and elevators (R, S, T) in different ways. ‘*Incisive*’ tongs (X) and ‘*a vis*’ (V) for fragments. Chisel (Δ) and hammer (Z). Figure XXXI (‘*Pour le trépan*’) is accompanied by the following description of the use of the instruments and the general surgical technique: ‘There will be a fire in a stove (B) in the bed and it will light up with two spark plugs (A), so as not to give two separate lights. The wound is discovered and cleaned with a cloth (C) and both ears are plugged with two cotton balls (DD). The edges of the cross wound can be kept open with cloth bands (EEEE) held by assistants. The crown of suitable size is chosen, large (F), medium (G) or small (H). Take the brace (I) and mount a perforator (K) and make a small hole in the bone giving four or five turns, where then the pyramid of the crown (L) is supported. There is a key to fix the pyramid (M), a probe to explore the depth of cut of the crown (P), a *“tirefond”* (O), an elevator (q) and a dissector in myrtle leaf (R) to lift the bone disk, a lenticular knife (S) and a brush (N). The lenticular instrument (T) serves to press the dura mater against the brain and let the blood out and absorb it (V)’. Finally, Fig. XXXII (‘*Pour le pansement du trépan*’) shows the trepanation dressing, drawing a number of fabrics, bandages, caps, sponges and other elements for dressing the trephine wound.

Another example of aggressive author concerning the indication of trepanation was Auguste Belloste (1654–1730), who belonged to the same line of French surgeons from the beginning of the eighteenth century. However, his contribution to this topic was an original method for treating the osseous defect caused by the trepanation. He used a lead sheet (although it could also be made of gold or silver) to cover the dura mater, which was exposed after the trepanation. It should be remembered that the surgeons resected a scalp circle to expose the fracture and carried out the trepanation without replacement of the bone. The sheet was well polished and drilled in many places. The sheet had the same size than the osseous defect and he cut it by using the trephine crown that he had previously employed as a template. This sheet had two wings. Once it was placed on the dura mater, he bended its wings so that they could adjust to the bone margins and the edges were applied on the surface of the skull. He explained some advantages of using this protection, such as allowing to drain blood or pus and to apply dressings so that they got soaked with the wound exudates, applying pastes with drugs, protecting the dura mater from its injury as it pressed against the margins of the trepanation and preserving the dura mater and the brain from the air. Finally, the sheet was removed when it was no longer useful.

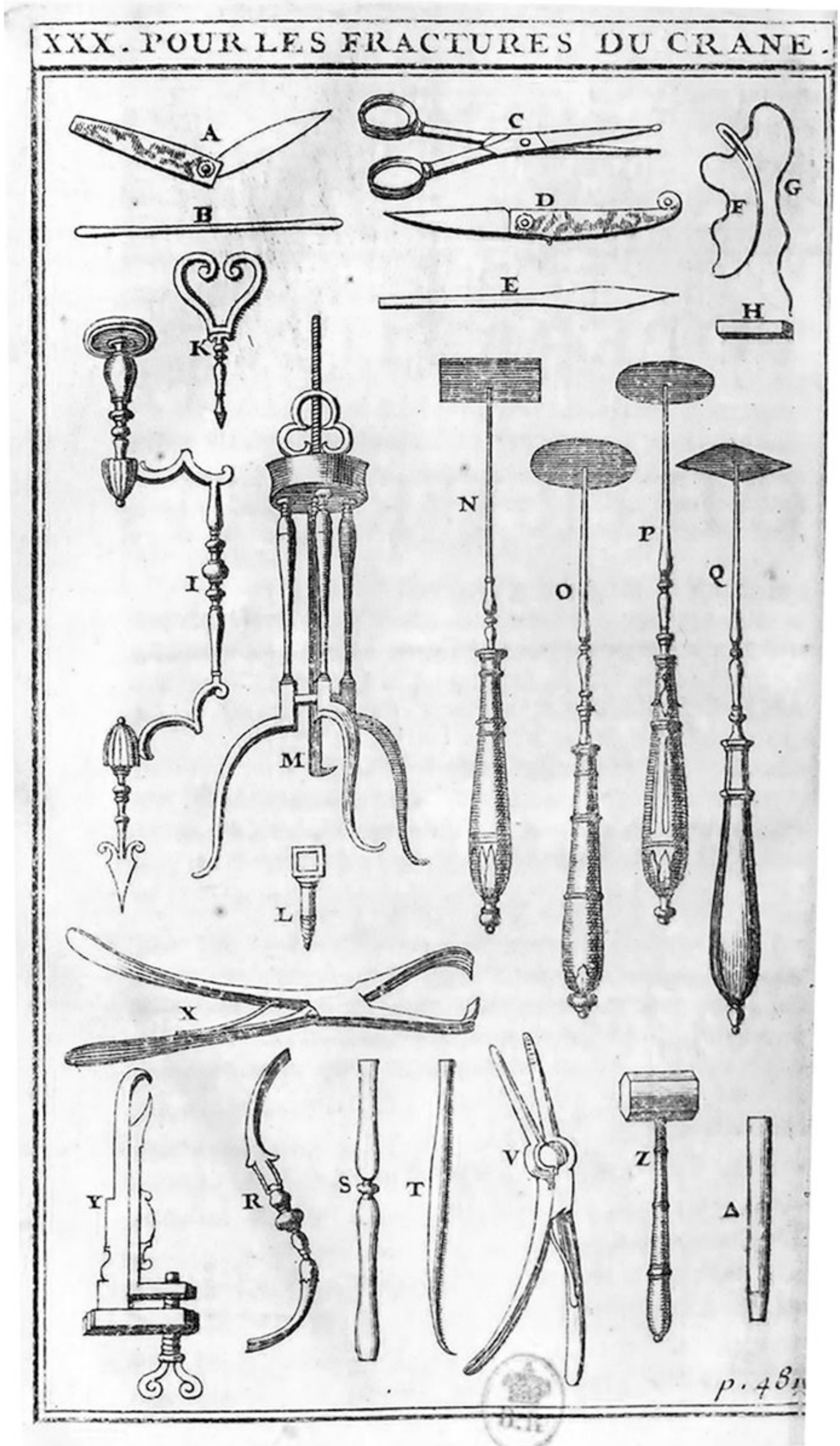

Fig. 16.1 Instruments related to trepanation by Pierre Dionis (Dionis, P. Cours d'operations de chirurgie. Démontrées au Jardin Royal. Paris: Chez d'Houry; 1740)

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tenir un air moderé. Le Chirurgien diſpoſera l'appareil, qui conſiſte en premier lieu aux inſtrumens dont il a beſoin pour faire l'opération. Secondement aux choſes néceſſaires pour panſer après l'opération; c'eſt pourquoi il aura deux baſſins, dans le premier il mettra les inſtrumens que vous voyez ſur la planche XXXI. & dans le ſecond tout ce qui pourra ſervir au panſement, & que je vous montrerai ſur la planche XXXII. De l'appareil.

FIG. XXXI. POUR LE TREPAN.

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Fig. 16.1 (continued)

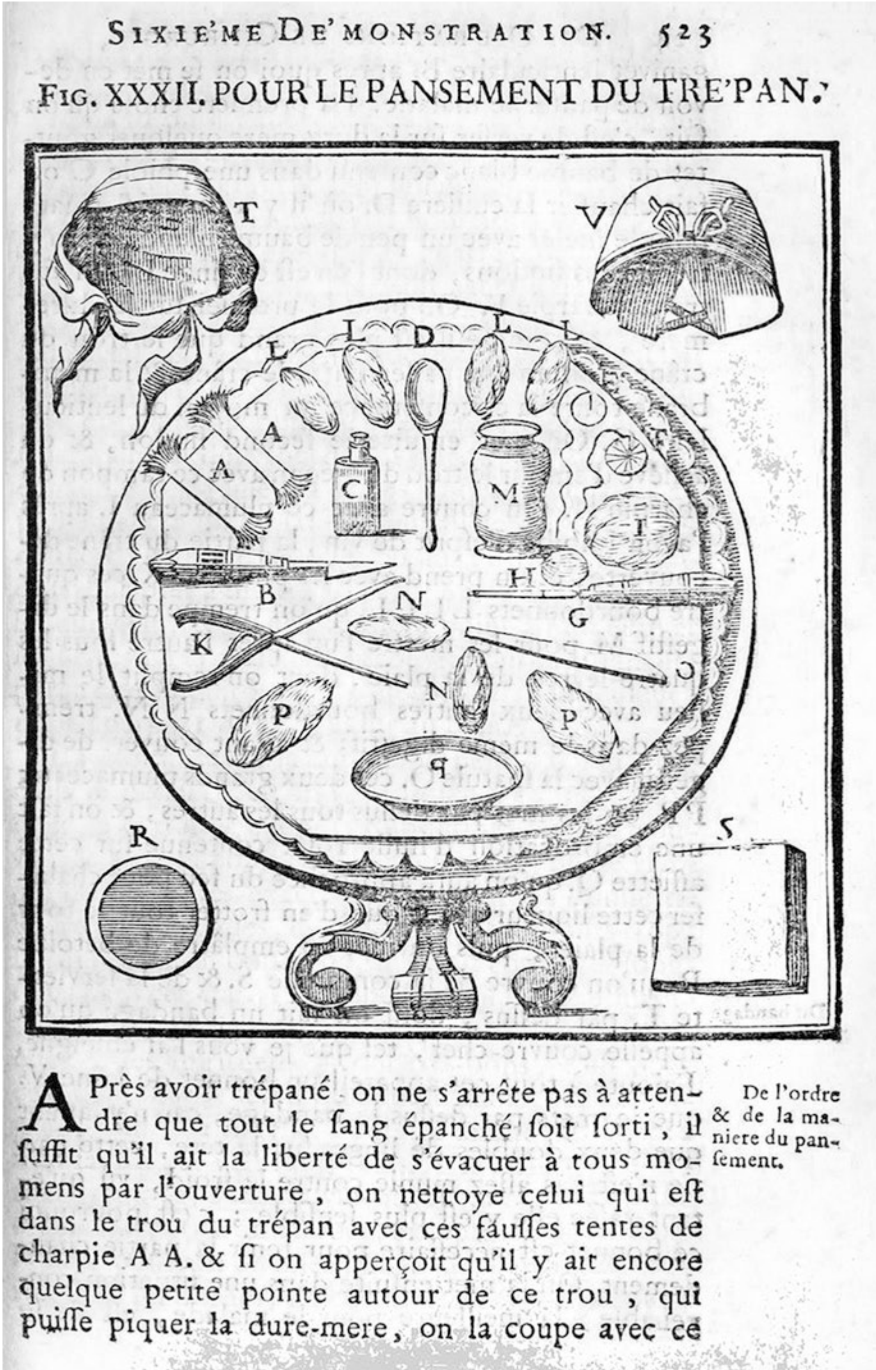
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FIG. XXXII. POUR LE PANSEMENT DU TRE'PAN.

APrès avoir trépané on ne s'arrête pas à attendre que tout le ſang épanché ſoit ſorti, il ſuffit qu'il ait la liberté de s'évacuer à tous momens par l'ouverture, on nettoye celui qui eſt dans le trou du trépan avec ces fauſſes tentes de charpie A A. & ſi on apperçoit qu'il y ait encore quelque petite pointe autour de ce trou, qui puiſſe piquer la dure-mere, on la coupe avec ce

De l'ordre & de la maniere du panſement.

Fig. 16.1 (continued)

Another French supporter of trepanation was François Quesnay (1694–1784), who admitted that there were cases in which trepanation could be avoided but they were infrequent and required a good judgement. Quesnay stated that the risks of a trepanation were lesser than the risks of not trepanning the patient. He published cases from his clinical experience, with 13 trepanations among 37 cases and a global mortality of 30.5%. The French surgeon Henri François Le Dran (1685–1770) was a great supporter of trepanation in depressed fractures and cranial fissures in that time to avoid the inflammation and decomposition of the dura mater. As many others, he considered more dangerous the narrow fissures than the wide ones, which allowed the fluids to come out more easily. In spite of that, his published experience was limited to 4 trepanations among 14 cases, with a global mortality of 57.1% among all treated patients. Other French surgeons of that time also supported an almost indiscriminate trepanation for all cranial traumas, such as Mauquest de la Motte (1655–1737) and René-Croissant Garengeot (1688–1759) himself. However, the most representative figure of this trend was the English surgeon Percivall Pott.

Percivall Pott (1713–1788) is the surgeon who represented the most aggressive point of view in terms of indication of cranial trepanation [4]. Pott was born in London and started as a surgeon apprentice at the Saint Bartholomew's Hospital in London in 1729, where he worked as a surgeon from the end of his training period in 1736 to his retirement in 1787. He died of pneumonia a year after. Pott is worldwide known for his description of the paraplegia associated to spinal deformities due to a tuberculosis infection. We have reviewed his book *'Observations on the nature and consequences of the injuries to which head is liable from external violence'* published in 1760 and re-edited in 1760.

Pott is always given as an example of an unconditional supporter of trepanation in skull trauma. He even affirmed that in those cases of trauma with non-depressed fractures or without concussion, inflammation or compression symptoms a trepanation must be carried out, not of necessity or as a treatment method of choice but as a preventive treatment. He was self-critical with his proposals and discussed the complications that could happen if the patient was not trepanned, the complications of trepanation, and the assessment of those cases that were saved thanks to the trepanation and those who died of it. However, at the end, he writes a vehement conclusion in which he reaffirms his convictions. He recognised that, in any case, patients who underwent trepanation healed later than those who underwent a conservatory treatment. He said that it was due to the fact that the dura mater and the tissues contacted with air. The reasoning process that allowed him to come to these conclusions was the following: the trauma and the cranial fracture made the bone to separate from the periosteum, which devitalised and discoloured the bone. Finally, the epidural space and the dura mater became decomposed and it caused fever, headache and coma. The trepanations by removing the bone would relieve the problem and the deleterious consequences. His published experience included 43 patients with 29 trepanations and a global mortality of 51.1% among the attended patients.

Pott was also a supporter of trepanation with a trephine crown and T-handle, just like his masters. Actually, other British surgeons endorsed similar proposals previously, such as Guillaume de Cheselden (1688–1752) from the Saint-Thomas Hospital in London. He eliminated the brace handle from the hospital and substituted it by the T-handle, which allowed him to successfully trepan on the sagittal sinus.

The general treatment protocol suggested by Pott was the following. If there was no wound on the pericranium or if it was so small that it did not allow to examine the bone or apply a trephine the surgeon carries out a circular resection of the pericranium with a knife until reaching the bone (*'there can be no doubt about the greater propriety of removing a piece of then scalp for this purpose'*). This procedure was called *'scalping'*. The trephine was applied covering the whole fracture or in such a way that the trepanation fell within the fracture line. The surgeon made as few trephine holes as possible to extend the cranial opening along the whole length of the fracture.

The trephine aimed to remove the bone fragments or eventual epidural accumulations. The moment when a trauma was trepanned could be similar to a primary treatment. However, it was often some kind of intermediate treatment, i.e. due to the problems arisen from the evolutionary phase of the trauma. Another trephination could be carried out if there was a poor later outcome. He described cases of trepanation on the sagittal suture with preservation of the sagittal sinus and removal of bone fragments from inside against the widespread point of view of that time. However, if foreign bodies were noticed in the brain after the trepanation and the epidural space examination, they were left intact as *'the surgeon has done this duty'*. He concluded that *'the rest we leave to heaven'*. When there were symptoms of neurological affectation and the surgeon had already trepanned on the area the fracture without finding anything and the patient showed a poor evolution, the surgeon was allowed to trepan on another point away from the trauma as long as there is *'the smallest degree of wound or bruise …; but where there is no local indication where to operate, I cannot see any vindicable for operating at all'*.

Following this concise and direct style, Pott includes only a figure of instruments for trepanation (Fig. 16.2). On page 123 of the text the author draws a trepan with a T-arm, with a variable position crown that slides along the central stem ending in a point. Next to it, a dissector is drawn. In the text, Pott emphasises that to make a trepanation: *'we now require only a trephine of such a side to remove a sufficient quantity of bone at once, and an elevator; or perhaps, now and then a pair of scissors'*.

This aggressive trend was soon criticised by some French surgeons. However, some of them started being strong supporters of trepanation. Jean-Louis Petit (1674–1750) was one of the most important anatomists and surgeons in France. He was recognised for being the inventor of the tourniquet. He was appointed the director of the French National Academy of Surgery when it was founded in 1731. His disciple M. Lesne (1722–1800) published his posthumous work *'Traité des maladies chirurgicales et des operations qui leur conviennent'* in 1733 [5]. What relates to the wounds of the head appears in a posthumous addendum entitled *'Supplément au traité des maladies chirugicales de M. Petit: Chapitre Des Plaies de la Tête'*.

Petit described first all types of head wounds and fractures and their symptoms in a very detailed way and then accurately assessed the indications and contraindications of trepanation. Petit opened the door to detractors of trepanation when he paid attention to the wound and the fracture as direct consequences of the trauma and when he separated the symptoms of concussion, inflammation and compression as independent clinical elements when it came to making a surgical decision. Hence, he highlighted that the concussion as a direct consequence of trauma often resolved spontaneously. However, the patient does not recover if there are other complications caused by the trauma, such as intracranial effusions.

When discussing the indications of trepanation, he initially said that *'l'operation du trépan n'est point mortelle par ell-même'* ('The operation of the trephine is not fatal by itself') and immediately affirmed that *'il est certain que plusieurs blessés qu'on a trépanés sans nécessité ont guéri'* ('It is certain that several wounded who were trepanned without need healed').

Petit argued that it was necessary to determine those cases that required trepanation. The indications of trepanation could be summed up as follows: cranial fracture is an indication of trepanation by itself; the situation of coma after a trauma is an indication of trepanation when it is caused by an effusion but it is useless in case of concussion; those situations with nosebleed, mouth or ear haemorrhage are not indications of trepanation by themselves as it is only indicated if there is a fracture or effusion; paralysis or convulsions are not indications of trepanation as it is only indicated if the patient shows effusion signs. Petit discussed each one of these situations and supported each conclusion with many clinical cases that he presented and discussed. As an interesting, technical anecdote, he recommended making a cross-shaped incision to look for the fracture and used the nails to remove the perios-

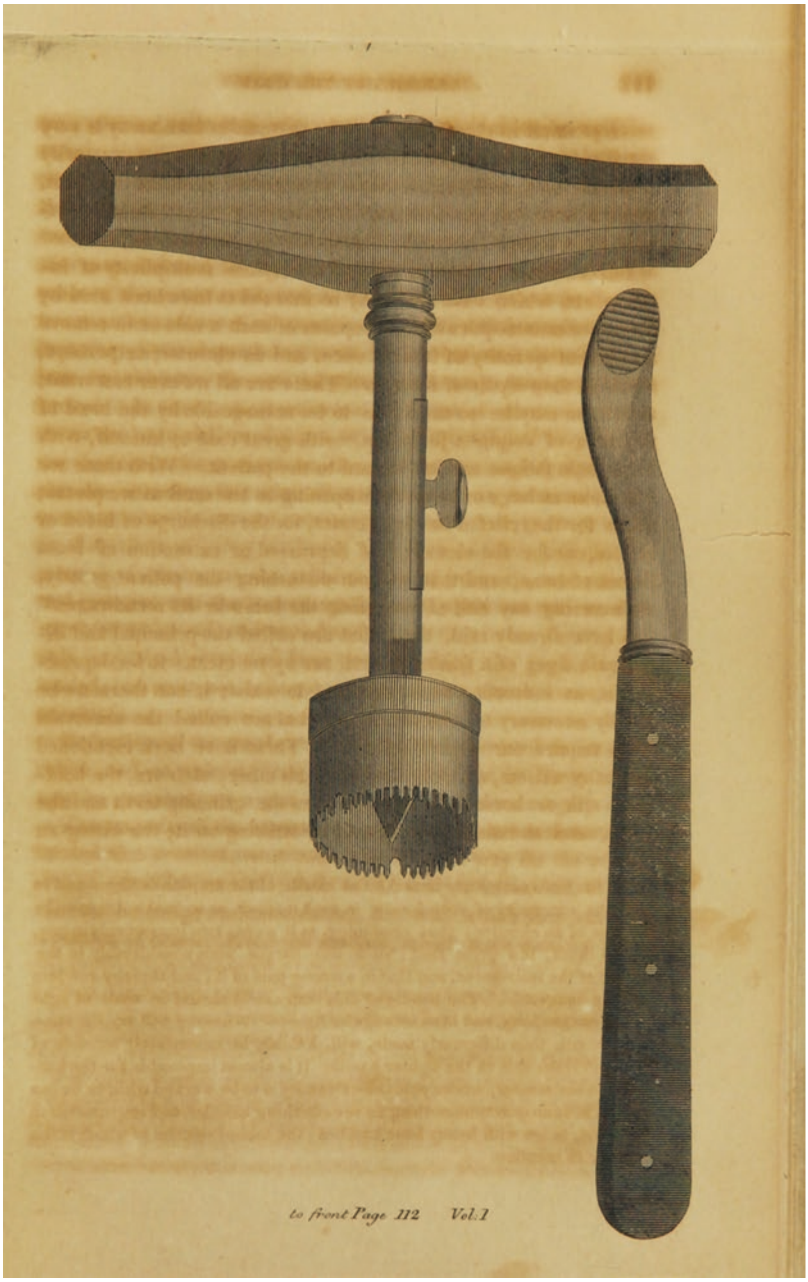


Fig. 16.2 Instruments related to trepanation by Percival Pott (Earle J. The chirurgical works of Percivall Pott: with his last corrections, to which are added a short account of the life of the author, a method of curing the hydrocele by injection and occasional notes and observations (vol 1). Philadelphia; James Webster. 1819)

teum more easily as *'l'ongle, comme je l'ai dit, est plus commode que le déchaussoir ou la rugine'* ('The fingernail, as I said, is more convenient than the elevator or the rugine').

Pierre-Joseph Desault (1738–1795) also was in the same direction favouring a selection of patients [6]. Desault was a French anatomist and surgeon who was initially trained as barber surgeon and became an apprentice of military surgery. He founded a school of anatomy and surgery on his own in Paris in 1766 and was finally accepted as a member of the association of surgeons. In the end, he was appointed Head Surgeon of the Hôpital de la Charité. He founded the *'Journal de Chirurgerie'* in 1791. He led a trend against trepanations and tried to raise awareness about the risks thereof and about the fact that it was often useless. He was a strong supporter of trepanations in all fractures with complications at first. He argued that it was better to run the risk of carrying out a trepanation as the patient might have an effusion if nothing was done. However, he defined and reduced its indications later and completely abandoned this procedure at the end of his professional life. His reasoning was based on the dangers of exposing the dura mater or the brain to the putrid air of hospitals and on the belief that the risk of cranial fractures was not the fracture itself, which could heal without requiring a trepanation, but the later consequences in terms of bleeding or infections that caused symptoms due to the brain compression.

He soon stated in the chapter on head wounds of his book *'Oeuvres chirurgicales de P.J. Desault'* published at the end of the century, in 1798 by *'son elève'* Xavier Bichat, that *'Je prouverai que l'indication du trépan n'existe jamais sans les accidens de la compression du cerveau'* [6]. His convictions on this issue were so solid that he affirmed that knowing whether the patient had a cranial fracture or not was not important. Therefore, he did not recommend exploring the wounds of the head or enlarging them or making cuts in order to find fractures in those cases with closed traumas or when a fracture by counterstroke was suspected. Even in those cases with compression symptoms there were so many doubts about the results of the trepanation that he affirmed that *'rarement il est indiqué d'ouvrir le crâne'*. After a long and exhaustive discussion and providing numerous arguments against trepanations on skull fractures he affirmed that *'1°. le trépan est très-dangereux par lui-même'* and secondly that in those fractures trepanned before the symptoms of compression appear, 'the trepan can sometimes cause these symptoms, it never prevents them, it rarely solves them and this only happens in those cases where they appear. For this reason, the trepanation is never indicated only for fractures and before the compression symptoms appear'. There is no point in trepanning in non-depressed cranial fractures with neurological manifestations due to a possible intracerebral, subarachnoid, subdural or epidural haematoma either. Sometimes the haematoma cannot be found or whenever it is found it cannot be evacuated. Also, whenever it is evacuated it does not involve any benefit for the patient. In addition to all this, the trepanation itself also involves some risks. The surgeon should not trepan looking for a haematoma in those cases with brain compression symptoms without an apparent fracture as he cannot be certain about the exact point to be trepanned. His own experience with ten patients at the Hôpital de la Charité and the Hôtel-Dieu made him affirm that he had forbidden trepanation in these situations 5 years before.

Desault admitted that a trepanation could be carried out in depressed cranial fractures to lift the fragments only when the compression symptoms were very severe and they were caused by such depressed bone fragments. Even though if the fragments could be lifted without trepanning, using for example the *'tirefond'*, this would be preferable. If there were no compression symptoms, depressed fractures should never be trepanned as *'le cerveau s'habitue peu à peu à la pression'*.

Hence, Desault wonders how to treat skull fractures. The author suggested using *'les évacuans, les stimulans, les saignées & autres moyens propres'*.

The main achievement of Desault and other French authors of that time was to separate the neurological symptoms, such as concussion and brain compression symptoms, from structural injuries, such as the wound of the pericranium and the skull fracture. The immediate loss of consciousness after the cranial trauma due to the drowsiness of concussion was also separated from the late reduction of the level of consciousness due to the complications of effusions. The French author Henri François Le Dran (1685–1770) clearly defined the concept of 'lucid interval' in that time. August Gottlieb Richter (1742–1812) was one of the most important figures against trepanation in Germany. He only justified it after assessing relevant clinical symptoms such as epileptic seizures with modifications on the heart rate and examining changes in pupil diameter and the patient's general condition.

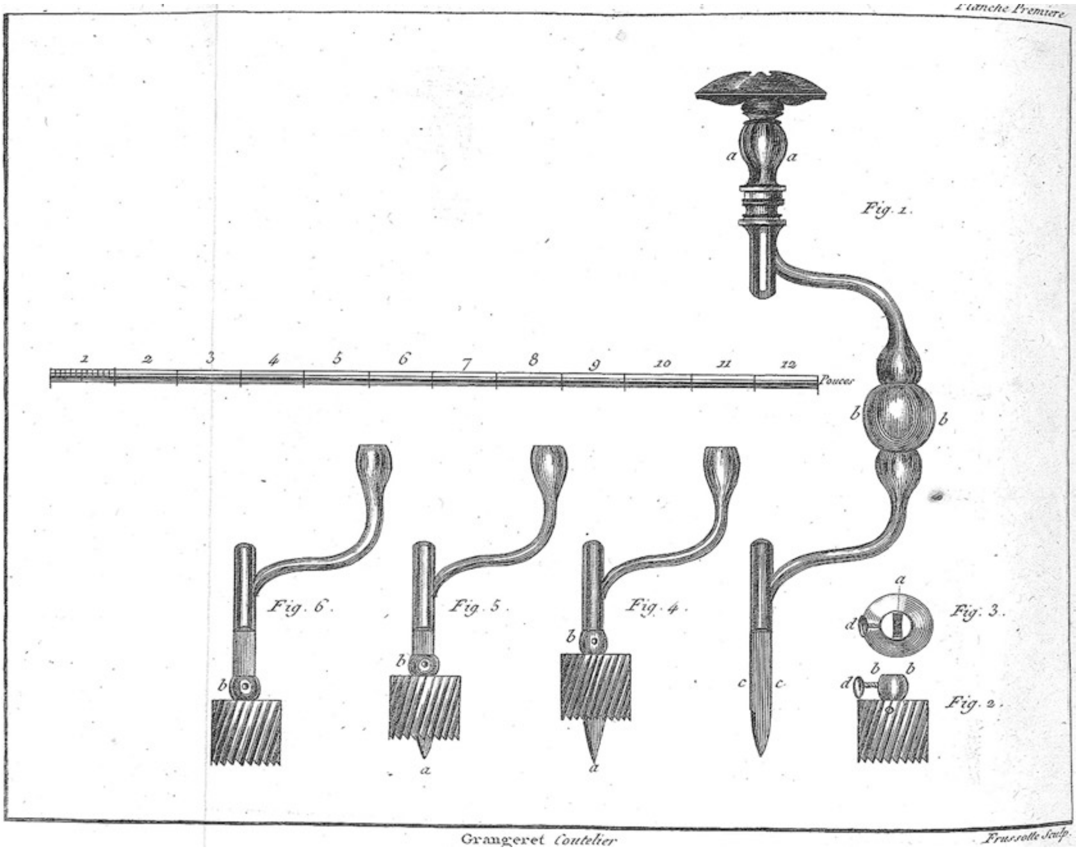


Fig. 16.3 Trepan invented by Xavier Bichat (Bichat, X. Mémoires de la Société médicale d'émulation: 2de année: articles divers. Paris: Maradan, 1799)

Desault's work was re-edited and completed with notes and comments after his death by one of his direct disciples, Xavier Bichat (1771–1802), in 1813 [7]. He reaffirmed his master's conclusions by describing new illustrative clinical cases. He affirmed that the indications of trepanation had been reduced to a *'très-petit nombre de cas'*. Curiously, Bichat added a chapter where he described the trepan and the trepanation technique in detail, as described years before [8]. He stated that ancient surgeons used up to 14 instruments for trepanning. Nevertheless, he considered that three of them were useless and did not include them in his instrument list. These three instruments were the *'meningofilax'*, the *'tire-fond'* and the *'exfoliatif'*. He described the typical French trepan of that time, with arm in brace and the cutting crown of variable position (Fig. 16.3). It had a brace handle, cylindrical interchangeable crowns with a grooved external surface and serrated edge, as well as a central pin or pyramid of different lengths where the crown runs along the pyramid. The author emphasises the economy in the number of pieces and innovations that facilitate trepanation and reduce surgical time. The legends in the original figure are as follows: Fig. 1. Trepan trunk: handle (aa), body (bb), tip welded to the body (cc) and carved in tip. Fig. 2. Crown: end (bb) drilled with an opening in which the fixed tip of the trunk engages, and fixing pin screw (d). Fig. 3. End of the crown, seen from above, with the opening (a) and the screw (d). Fig. 4. Trunk armed with the crown, mounted very high, so that in the first time the tip (a) can serve as a perforator. Fig. 5. Crown lowered on the trunk (b) so that, in a second time, the tip (a) replaces the pyramid. Fig. 6. Crown lowered to the maximum (b), so that it exceeds the level of the tip, so that it, in the third time, cannot hurt the dura mater.

16.3 The French Style of Trepanation

The French style of trepanation was defined at that time, not only around indications, but also using a particular set of instruments and a detailed step-by-step surgical protocol.

Jean-Louis Petit (1674–1750) described with great accuracy the instruments for trepanation in some beautiful plates included in the book *'Traité des maladies chirurgicales et des operations qui leur conviennent'*, published in 1790 by his disciple M. Lesne [5]. Now we reproduce and describe all these plates in Fig. 16.4:

– *Plate 4.* Fig. 1: Double lift, which is used above all to lift the sunken bone over the dura mater. Fig. 2: Spatula. Fig. 3: Double-myrtle leaf. Fig. 4: Scalpel spring, very strong.
– *Plate 5.* Fig. 1: Represents the trephine mounted with all its parts necessary for the operation. Fig. 2: Separate trephine knob. Fig. 3: Crown of the trepan. Fig. 4: Pyramid.
– *Plate 6.* Fig. 1: Key of the pyramid. Fig. 2: The *'tire-fond'*, with the spiral portion that is hooked in the hole made by the pyramid to raise or break the piece of bone formed by trepanation. Fig. 3: *'Perforative'* tip. Fig. 4: Crown of the disassembled trepan. Fig. 5: Trephine crown, with the screw that joins it to the shaft (A) and the spiral that joins it to the handle (D). Fig. 6: Demounted crown of trephine, with the holes (AA) through which the two screws (BC) pass which fix it to the shaft. Fig. 7: The axis without crown, with the pyramid (A), the coupling ring to the crown (B), the hole for the screw to fasten the crown (C) and the spiral to the handle (D).
– *Plate 7.* Fig. 1: Cap of the crown. Fig. 2: Crown of trepan with the saw and the pyramid. Fig. 3: Trepan *'perforative'*. Fig. 4: Trepan *'exfoliatif'*. Fig. 5: Teaspoon. Fig. 6: Brush to clean the crown.
– *Plate 8.* Fig. 1: Handheld trepan with transverse grip, with its crown. Figs. 3 and 4: Key (G) and pyramid (I). Figs. 2, 5 and 6: three trephines, crown with saw, perforating and exfoliating.
– *Plate 9.* Fig. 1: Elevator. Fig. 2: The same elevator mounted on a handle. Fig. 3: Parrot's beak (*'Le bec de perroquet'*) or incisive tongs to cut a piece of bone from the skull.
– *Plate 10.* Fig. 1: Lenticular knife, with the button (A) and the handle (D). Fig. 3: *'Meningophilax'*, whose function is to separate the dura so that the accumulated material leaves. Figs. 2, 4, 5 and 6: Different *'rugines'*.
– *Plate 11.* Three different instruments are represented that have the same utility as the lenticular knife, with different diameters for each size of the trephine's crown. There is also an elevating instrument.
– *Plate 13.* Fig. 1: The *'triploïde'* is represented, where the *'tire-fond'* is used to raise the sunken bone fragments. The three legs (1, 2, 3) are joined together with a screw to a plate (CC). The plate is perforated in its centre to make way for an axis (A) that is carved in thread pitch and goes down through another plate with the branches that form a tripod (FGH). The axis ends in a hook (D) that passes through the handle of a screw (E), which is shown separately in Fig. 7. Fig. 2: Piece of bone carved by the trephine crown, in the centre of which a hole has been marked in which the *'tire-fond'* has been hooked to elevate it. Figs. 3, 4 and 5: Simple, double or triple cutouts according to the number of trephines applied. Fig. 6: Small lead plate that is used after the trepan. Figure ABC corresponds to the shape for a wound treated by Petit.
– *Plate 14.* In this page are represented the frame elevators invented by Petit.
– *Plate 15.* Fig. 1: Ordinary simple elevator. Figs. 2, 3 and 4: Easels of different sizes on which the lever elevator of Fig. 5, which is of Petit's invention, is mounted.
– *Plate 16.* Fig. 1: Elevator invented by Petit, with the lever and easel. The mounted lift is shown in Fig. 4.
– *Plate 17.* Figs. 1, 2 and 4: Gouges in different ways. Fig. 3: Chisel. Fig. 5: Lead hammer.

From a technical point of view the French style of trepanation and instruments is well represented also by René-Croissant Garengeot (1688–1759),

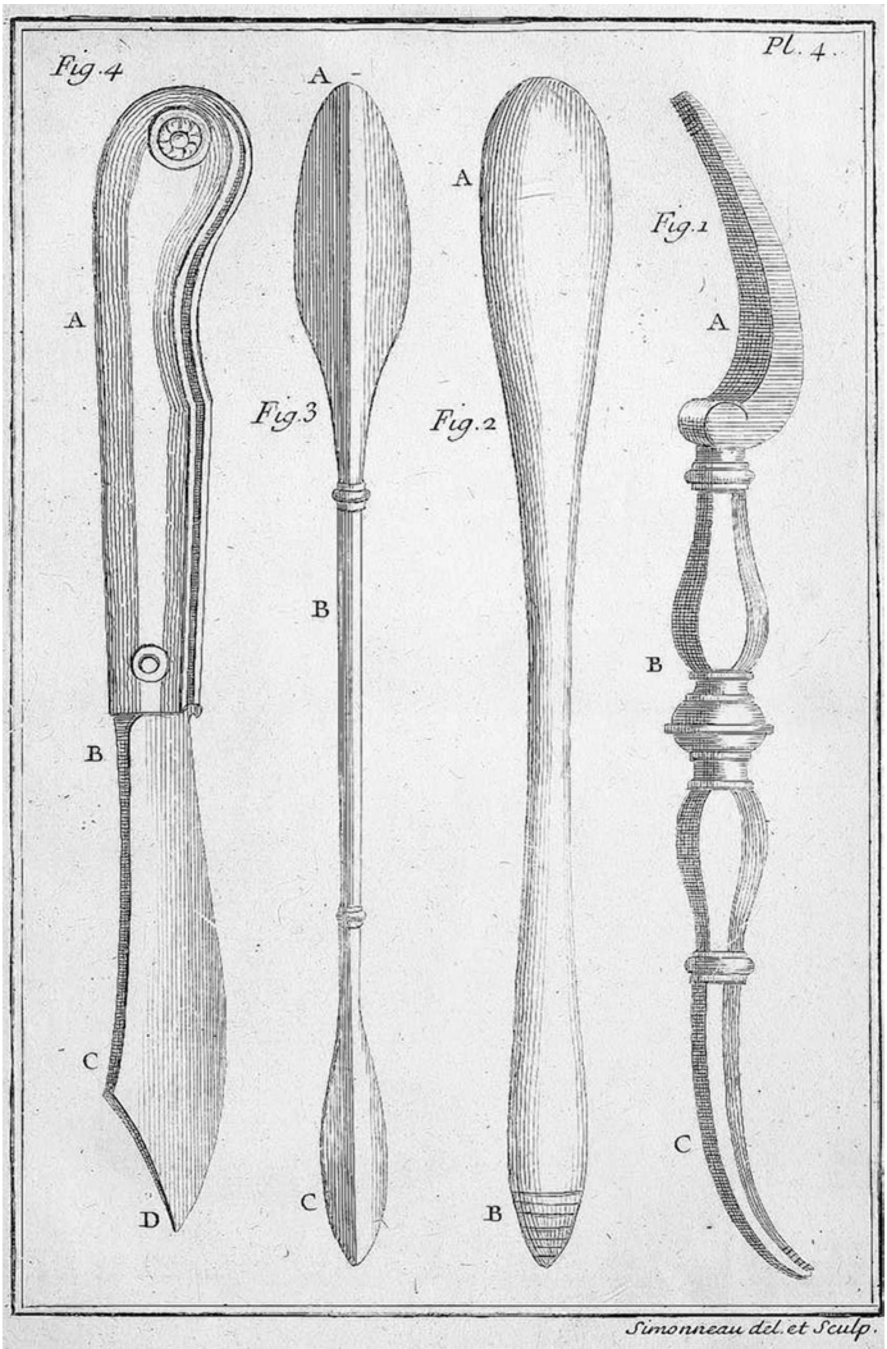
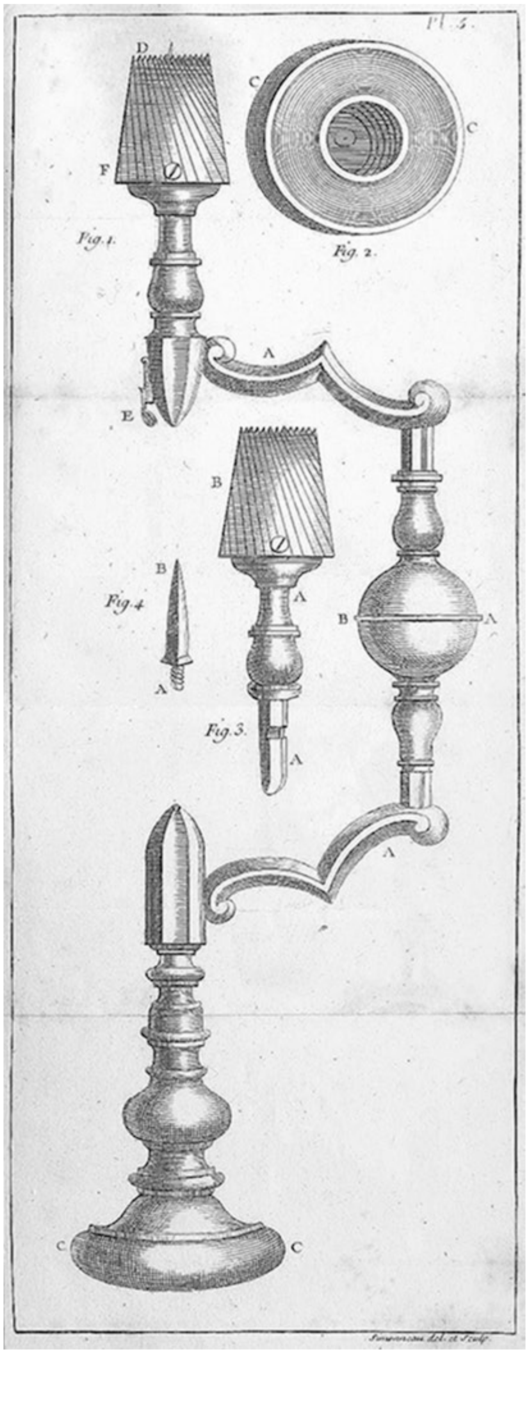


Fig. 16.4 Instruments for trepanation by Jean-Louis Petit (Lesne FD. Traité des maladies chirurgigales et des opérations qui leur conviennent. Ouvrage posthume de M.J.L. Petit. Paris: Chez Méquignon; 1790)



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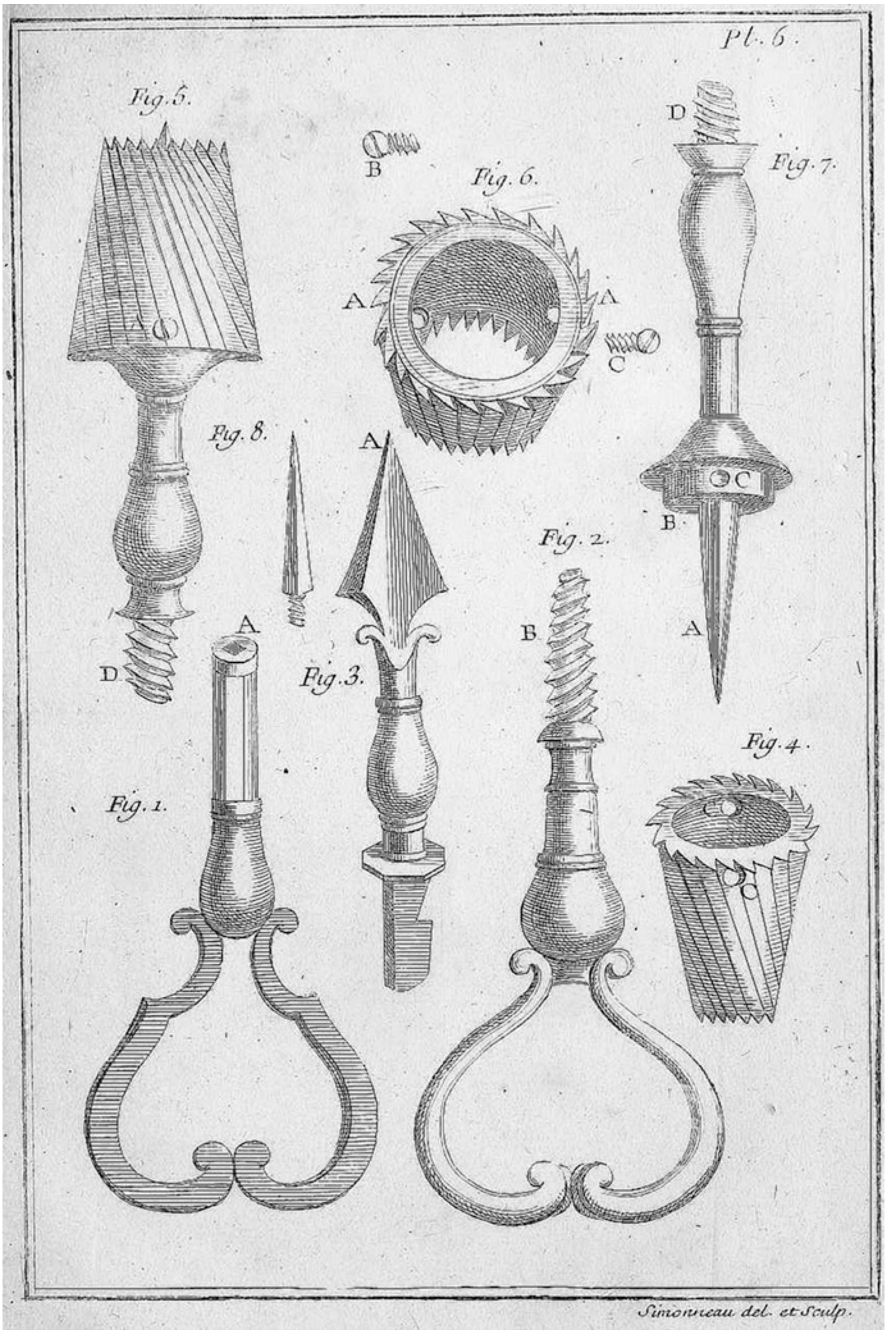

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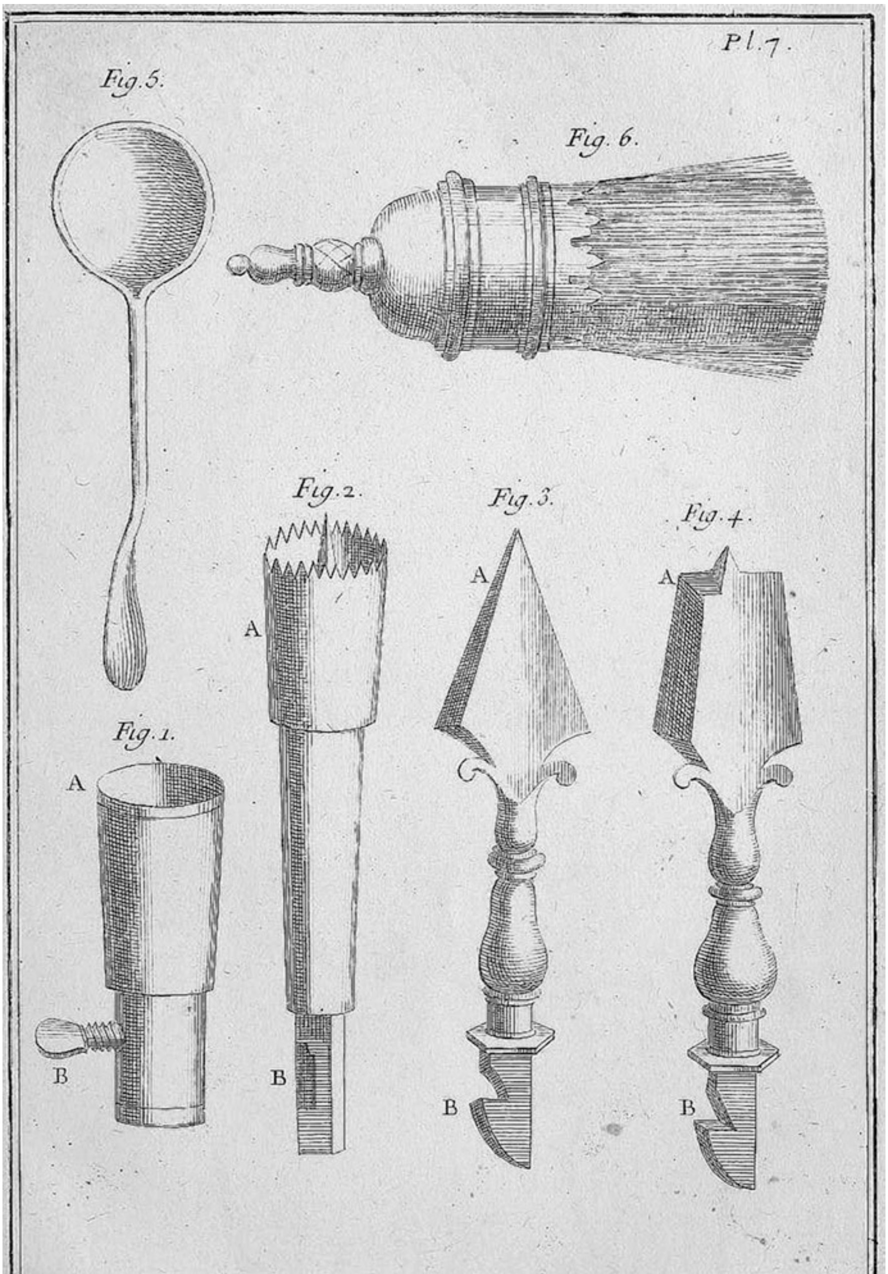

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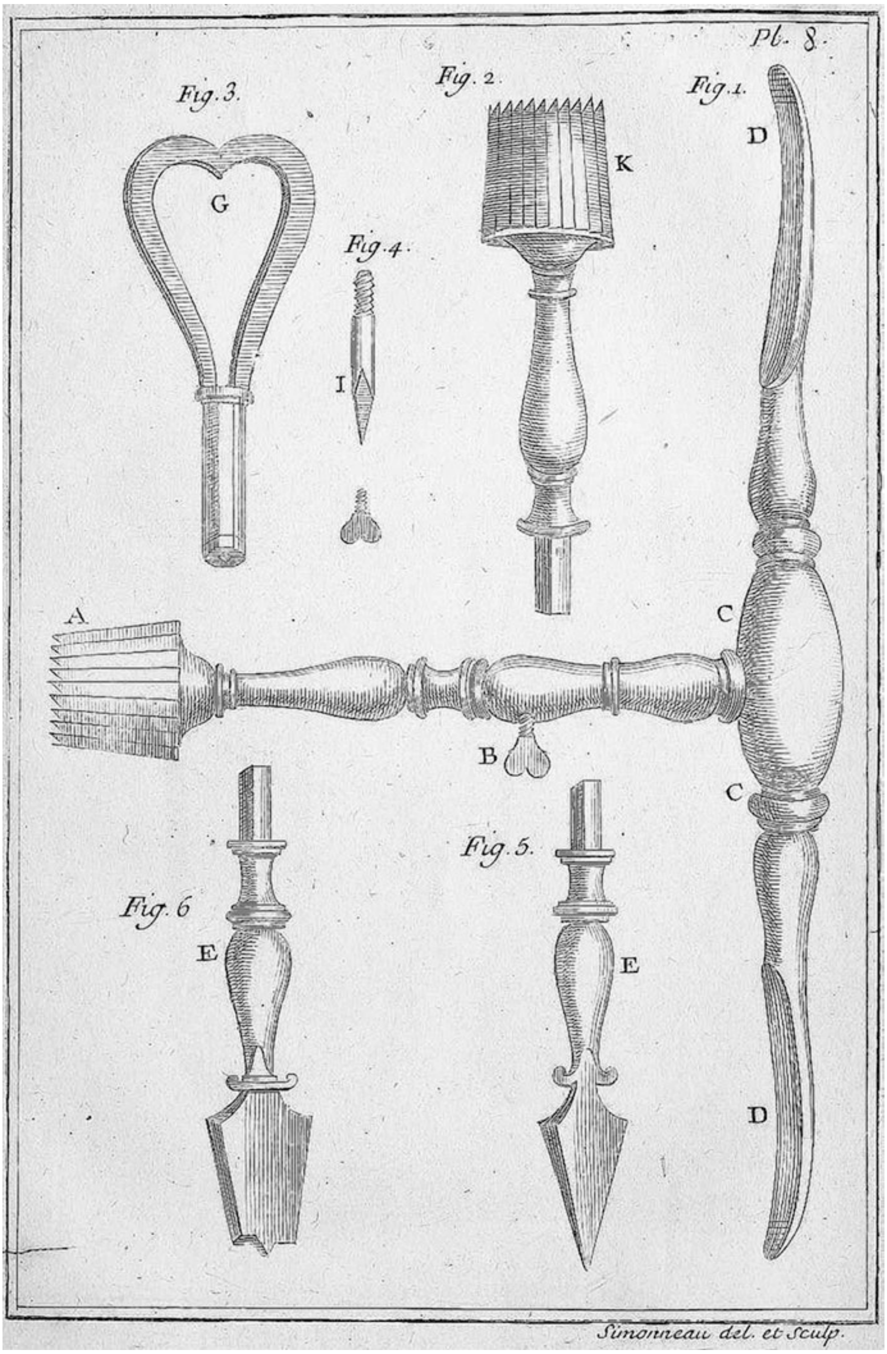

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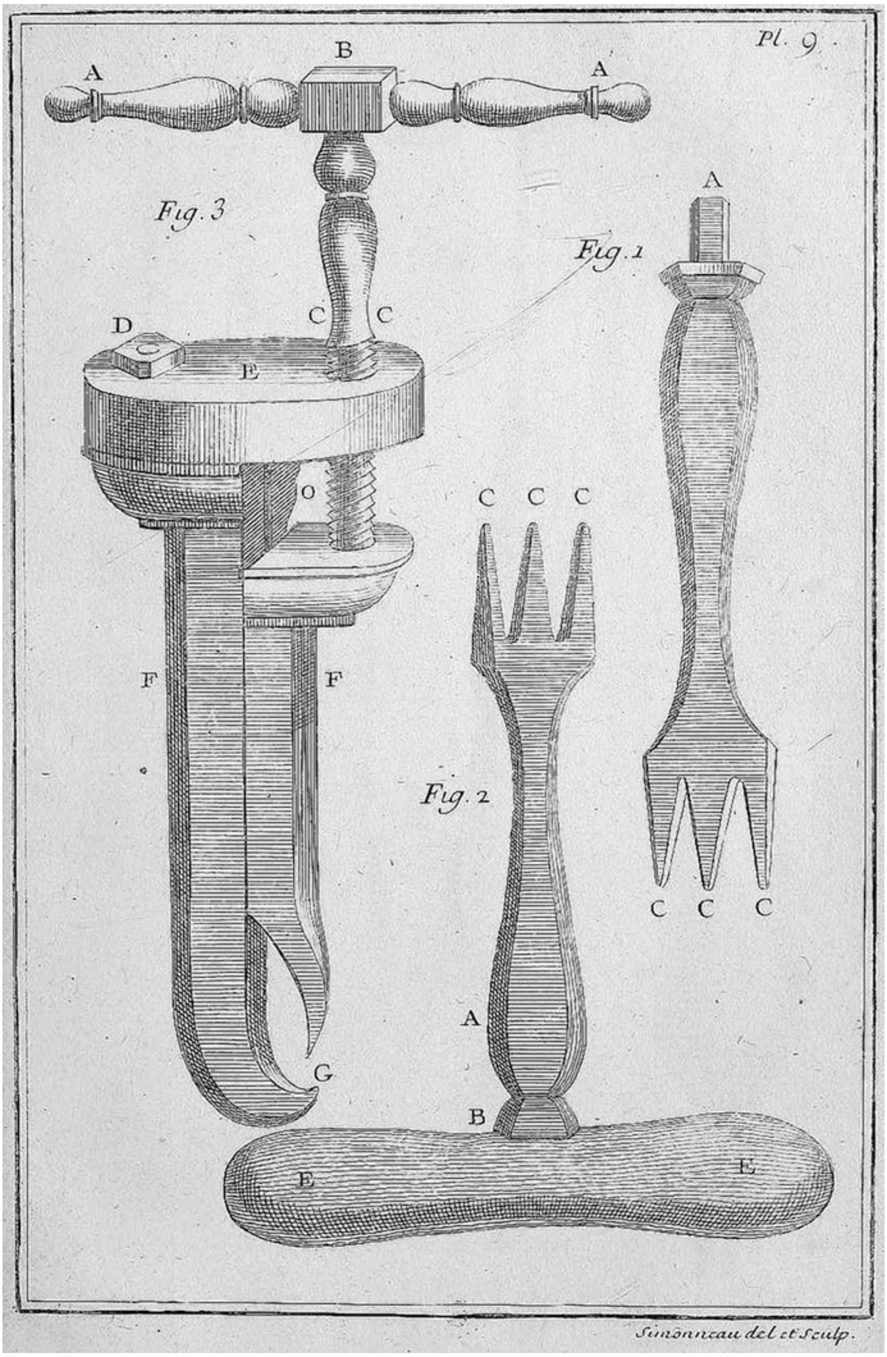

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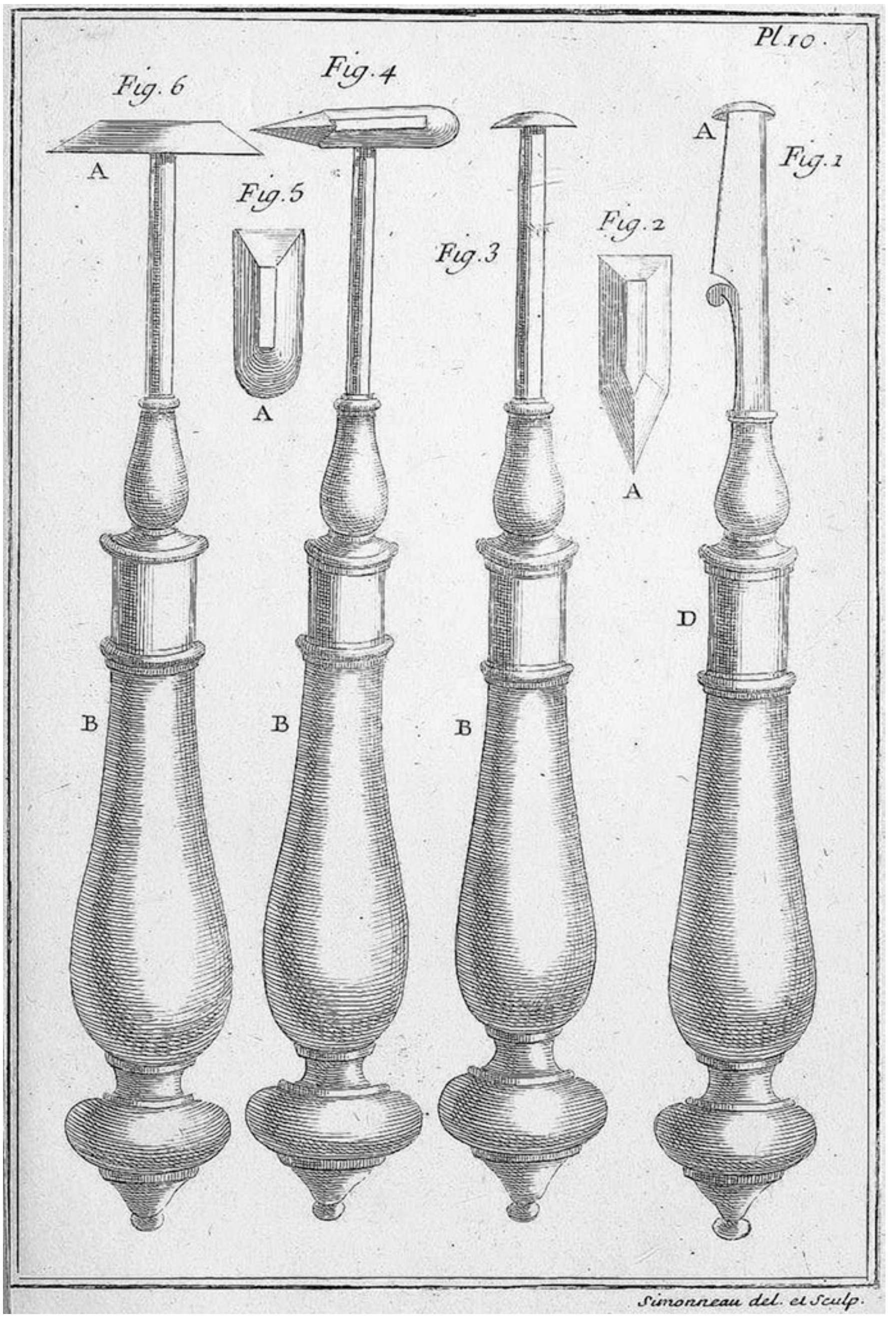

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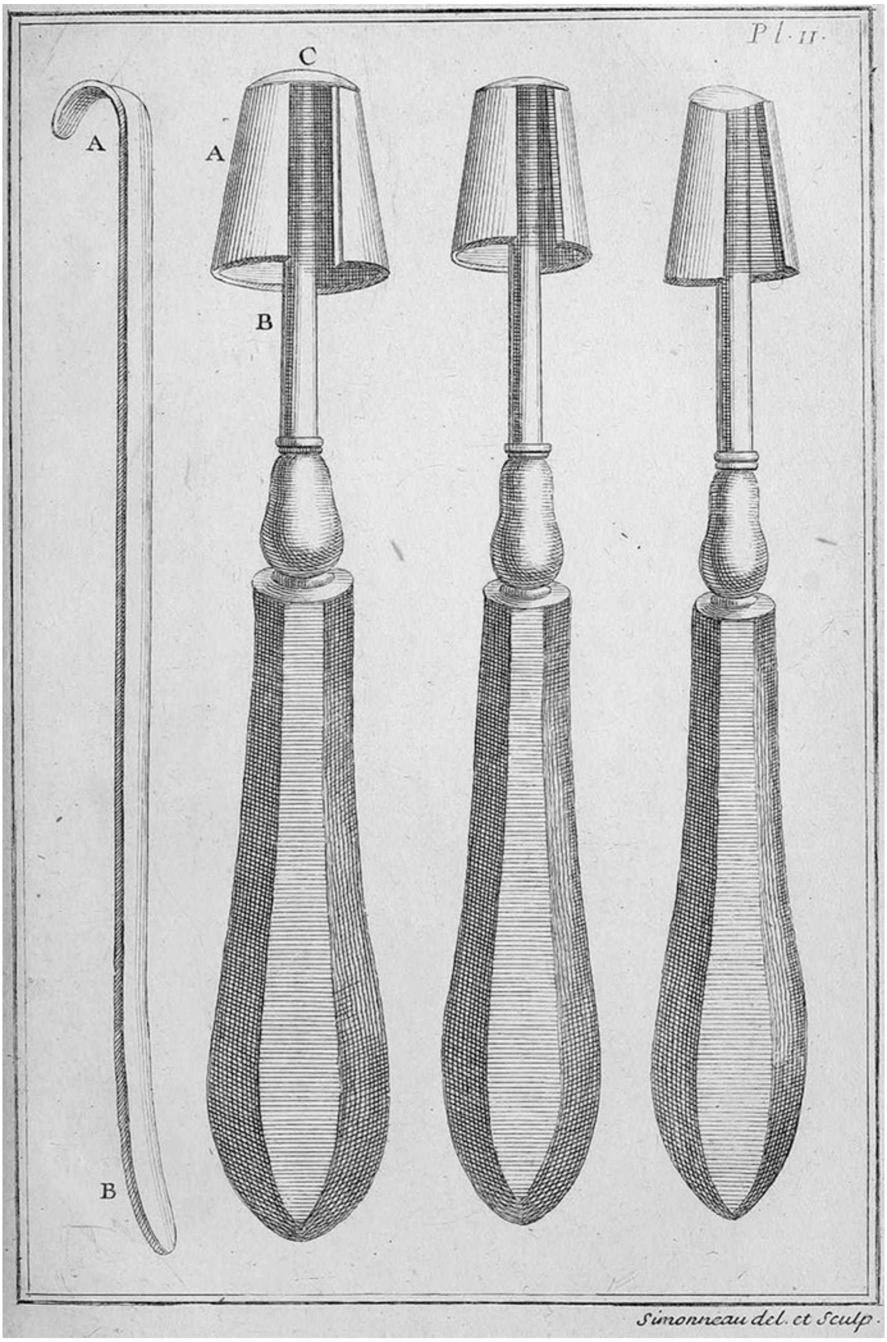

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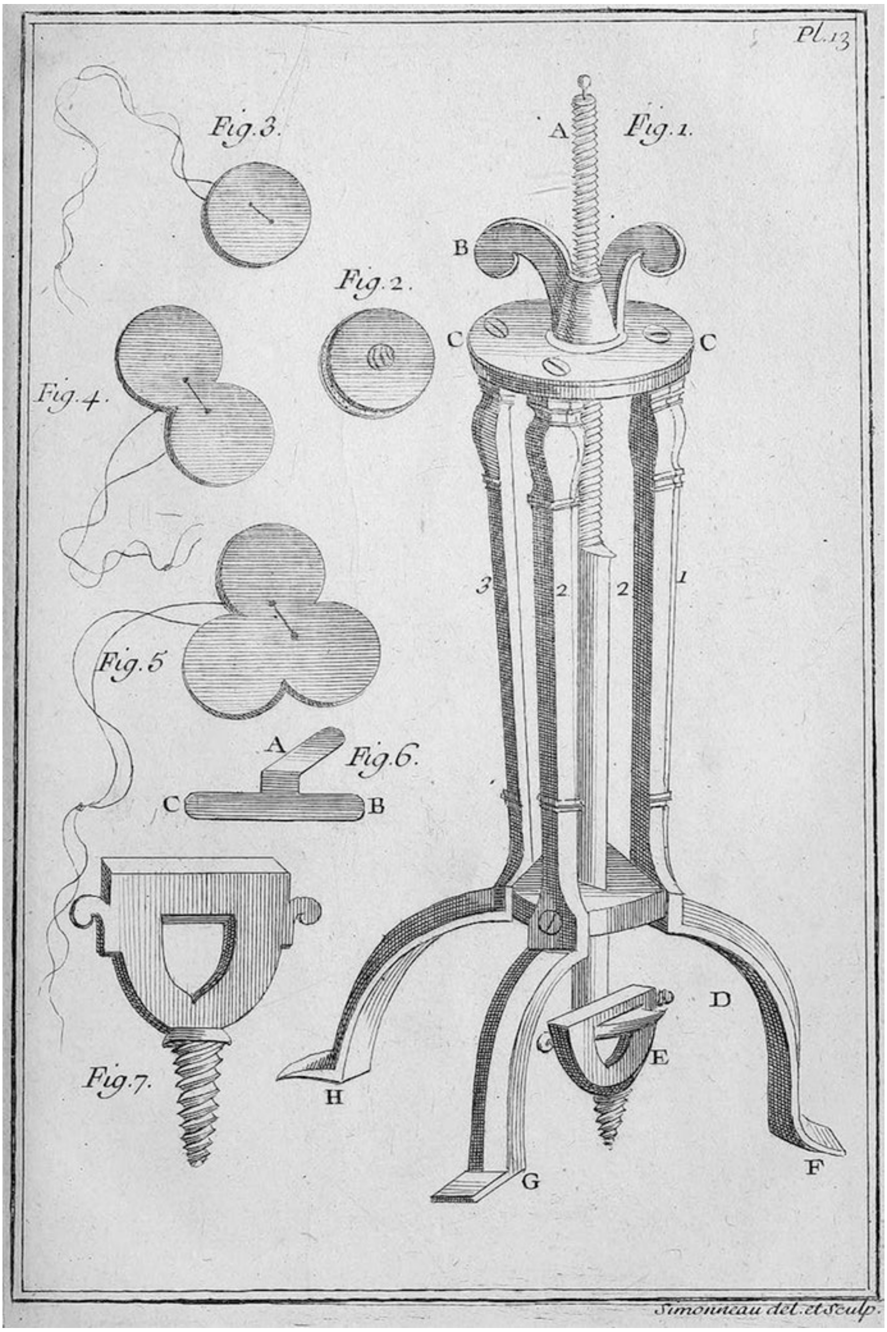

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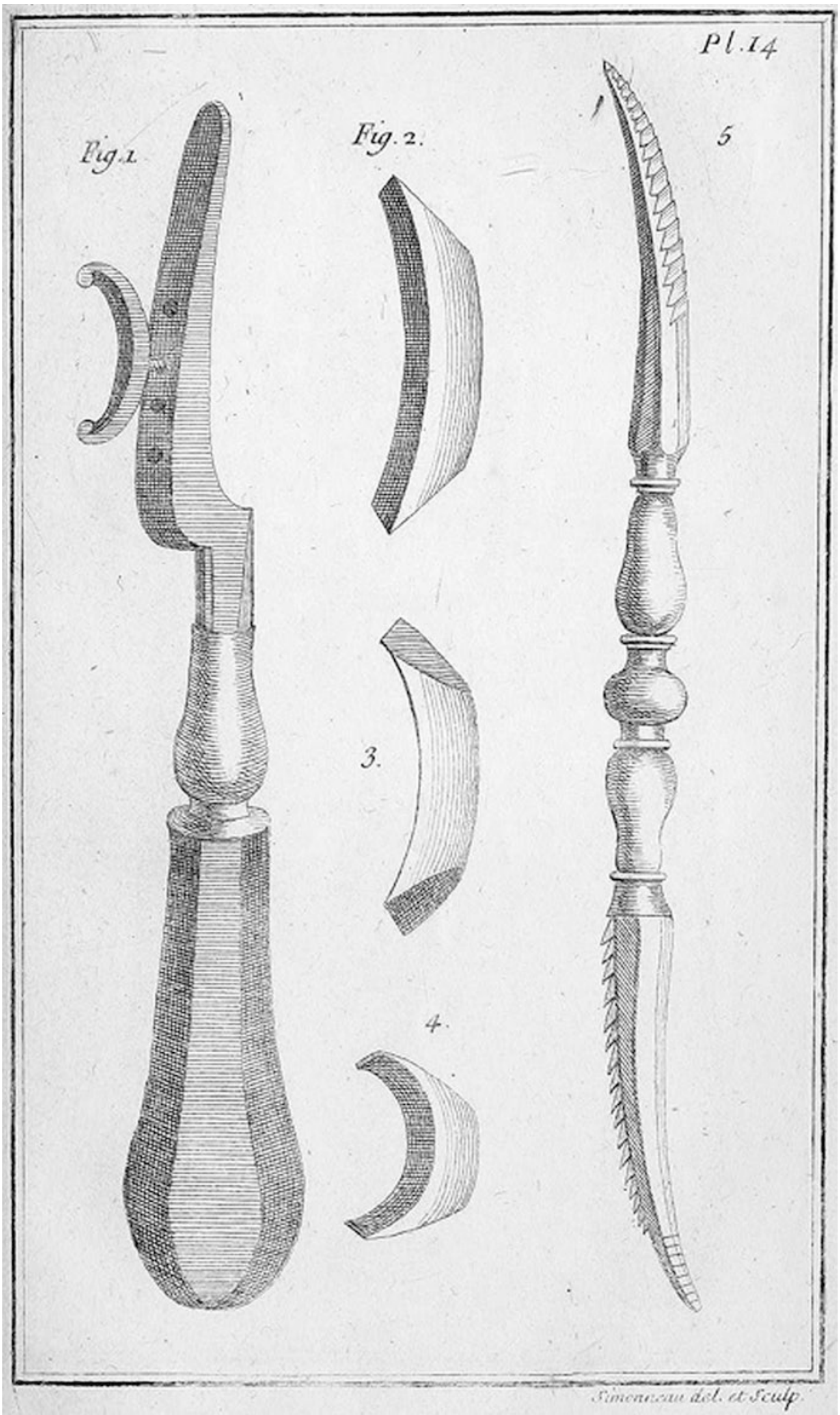

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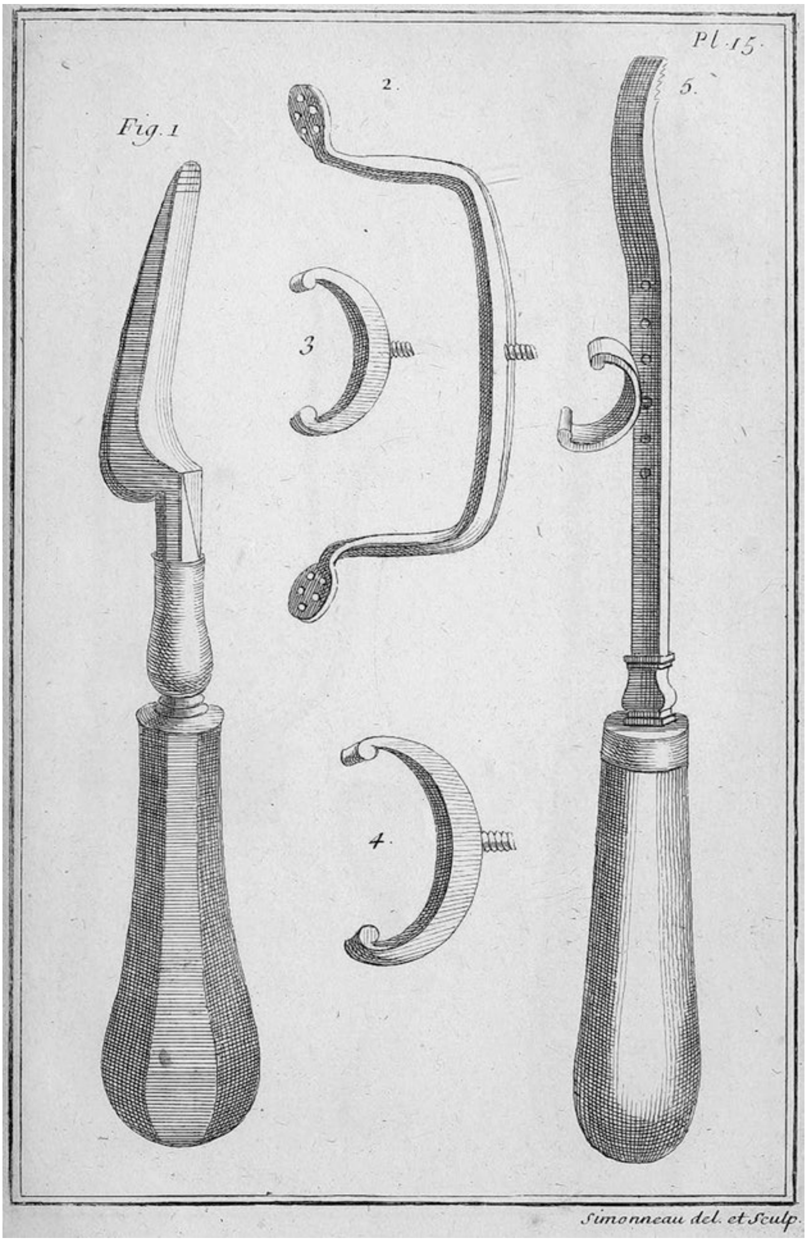

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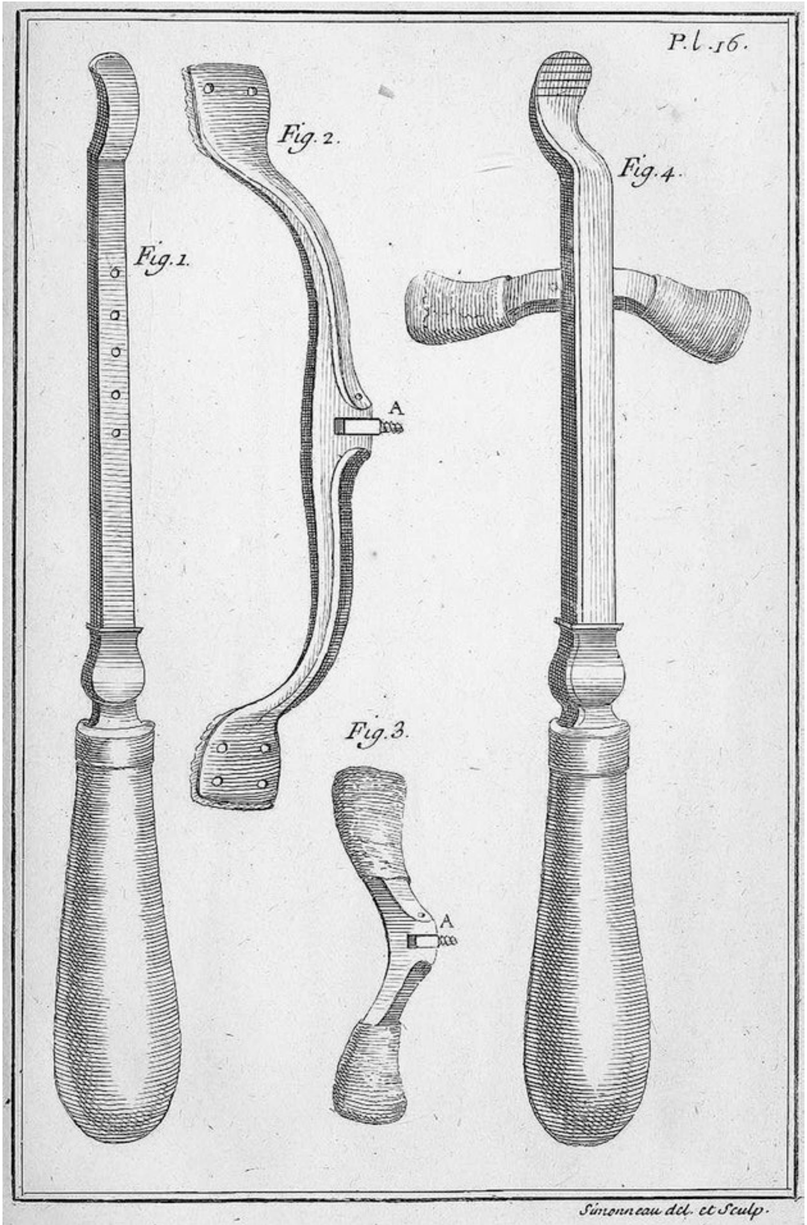

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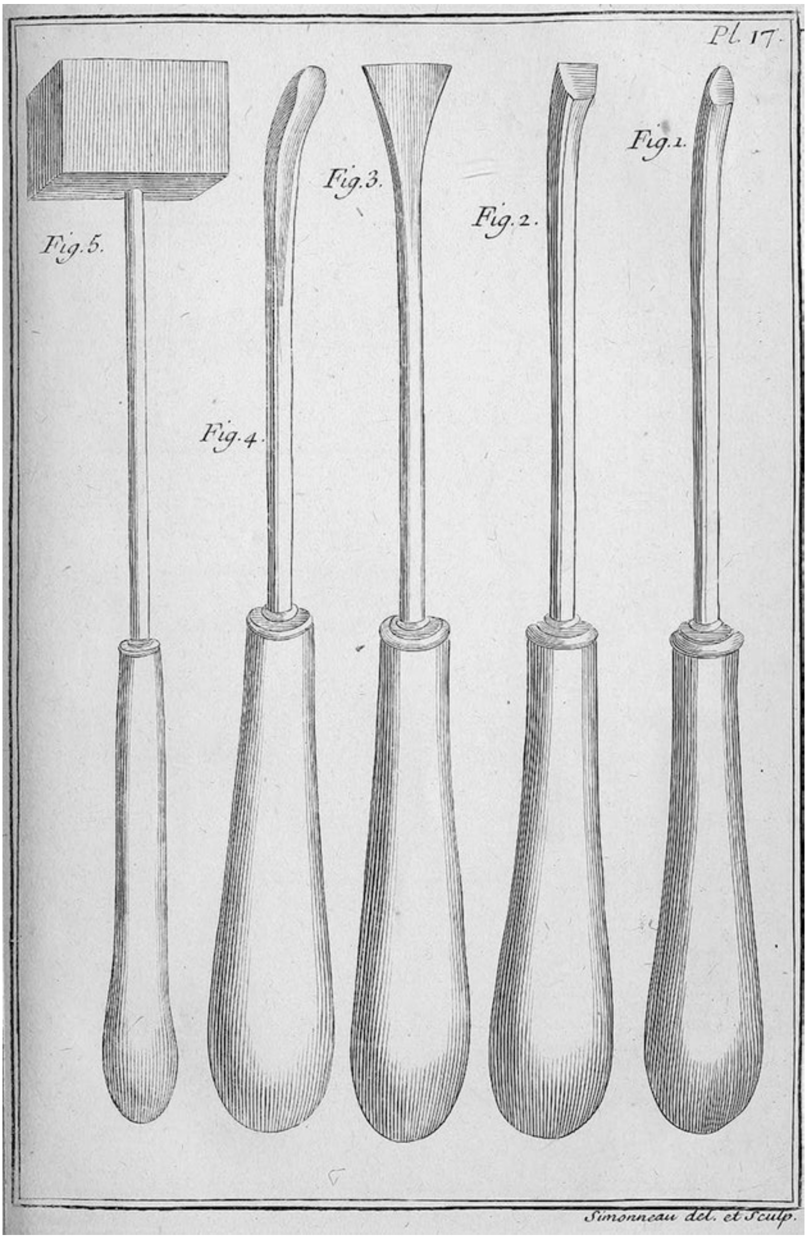


Fig. 16.4 (continued)

author of the book *'Nouveau traité des instruments de chirurgie les plus utiles, et de plusieurs nouvelles machines propres pour les maladies des os'* [9]. Along Chap. III (*'Des Instruments qui composent le Trépan'*) of the book, the instruments for trepanation are described, which are drawn in figures out of text. Garengeot indicates that the instruments are many so they are divided into three groups: those necessary to discover the bone, those needed to pierce or saw the bone and those used to cut the irregularities left by the crown and raise the pieces of bone depressed or sunken, aside from the common ones for any surgery such as shaver, scalpels or probes. The description that Garengeot builds in the text is neat, exhaustive and even obsessive in regard to the instrument, measurements, materials, details of manufacture, form of grip and use by the surgeon and particular utility of the described instrument. The plates have an explanatory foot of figure included in the text.

The specific instruments of trepanation are described individually in different articles. They are reproduced in Fig. 16.5.

– *Article I. 'D'un Scalpel en forme de fëuille de mirte, qui est prope pour enlever tout d'un coup la peau, les muscles & le péri-crane'* (On a scalpel in the form of myrtle leaf, suitable for cutting skin, muscles and pericranium all at once). The scalpel has a central stem that serves as a handle and a cutting blade at each end in the shape of a myrtle leaf (T-II-87, 3-f).
– *Article II. 'Des Rugines qui servent à decouvrir & ratiller les os'* (On the *'rugines'* that serve to discover and smooth the bone). They have an ebony or ivory handle and the steel cutting end. The handle is thick to achieve a good grip and has several faces for embellishments and ornaments. It describes two *'rugines'* of different shapes and that can be used in other bones of the organism (T-II-96, 1-f, 2-f).
– *Article III. 'Du Trépan en general, & particulariement de l'exfoliatif'* (On the trepan in general & particularly of the exfoliator) (T-II-96, 3-f).
– *Article IV. 'Du Trépan perforatif'* (Drilling trepan) (T-II-115, 1-f).
– *Article V. 'Du Trépan couronné, ou des couronnes du Trépan'* (On the crowned trepan, or crowns of the trepan) (T-II-115, 2-f).
– *Article VI. 'De la Clef du Trépan'* (On the key of the trepan) (T-II-96, 4-f).
– *Article VII. 'De l'Arbre du Trépan'* (On the handle of the trepan) (T-II-138, 1-f). In the previous sections the trephine is described as a brace of iron or steel formed by two pieces. One of them is truly the trepan, and the other is the brace or handle that sustains it. The trepan serves to perforate and saw the bones, mainly those of the skull. The trepan has three types of tip: exfoliating, perforating and crowned trepan or the crowns of the trepan, in number of three of different diameters, slightly trunk-conical to avoid that they sink, endowed with a central pin or pyramid (T-II -115, 3-f) and of different depths of cut. A key (T-II-115, 4-f) allows to adjust the pyramid in the centre of the crown. The handle (*'l'arbre du trépan'*) has the shape of a brace, like the one used by the carpenters, but endowed at its upper end with a wider part called a walnut where the user of the trepan can support the chin. The handle is made of ebony, ivory and steel. In these articles, each of the sections is described neatly. Also described is how the handle is used, with a description of the so-called chin support handling proposed by Monsieur Petit.
– *Article VIII. 'Du Tire-fond don't on se sert pour enlever la piece d'os'* (On the screwdriver that serves to elevate the pieces of bone) (T-II-138, 2-f). It is nothing more than a shank with a screw tip and that is inserted into the hole that has made in the bone the exfoliating trephine or the pyramid of the crown. It serves to lift the carved bone disc once the perforation is completed.
– *Article IX. 'Des Brosses qui sont propes pour nettoïer les couronnes du trépan'* (On the brushes that are appropriate to clean the crowns of the trepan).
– *Article X. 'Du Coteau lenticulaire destine pour couper les irrégalités que la couronne a laissées à la table interne du crane'* (On the lenticular knife intended to cut the irregularities left by the crown on the internal table of the skull) (T-II-152, 1-f). The instrument is constructed with a handle similar to that of the *'rugine'* and that in its lower end has a knife with its end equipped with a lenticular plate to protect the dura mater.
– *Article XI. 'Des Elevatoires'* (The elevators) (T-II-115, 2-f, 3-f). They serve to lift the pieces of sunken bone and resemble levers of first degree built with a central stem and the ends bent one on one side and the other on the other.
– *Article XII. 'Du Meningophilax'* (On the *'meningofilax'*) (T-II-158, 1-f). Gerengeot says that *'meningophilax'* is a Greek term that means 'guardian of the meninges' and that the design and use are different from those of the Greeks. The one that is described is a cylindrical

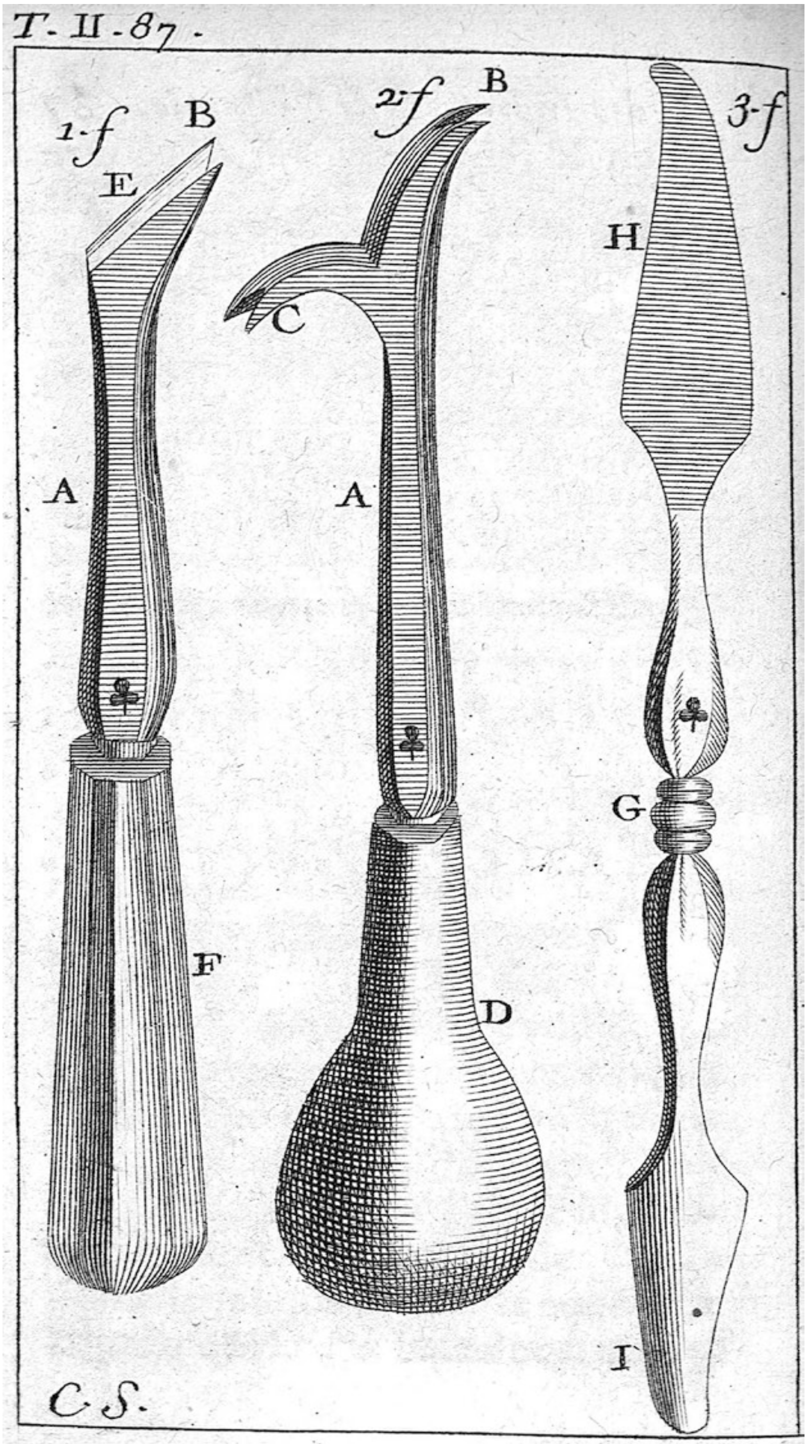


Fig. 16.5 Instruments related to trepanation by René Garengeot (Garengeot RJC. Nouveau traité des instruments de chirurgie les plus útiles et de plusieurs nouvelles machines propres pour les maladies des os (2nd ed). Paris: Chez Guillaume Cavelier; 1727)

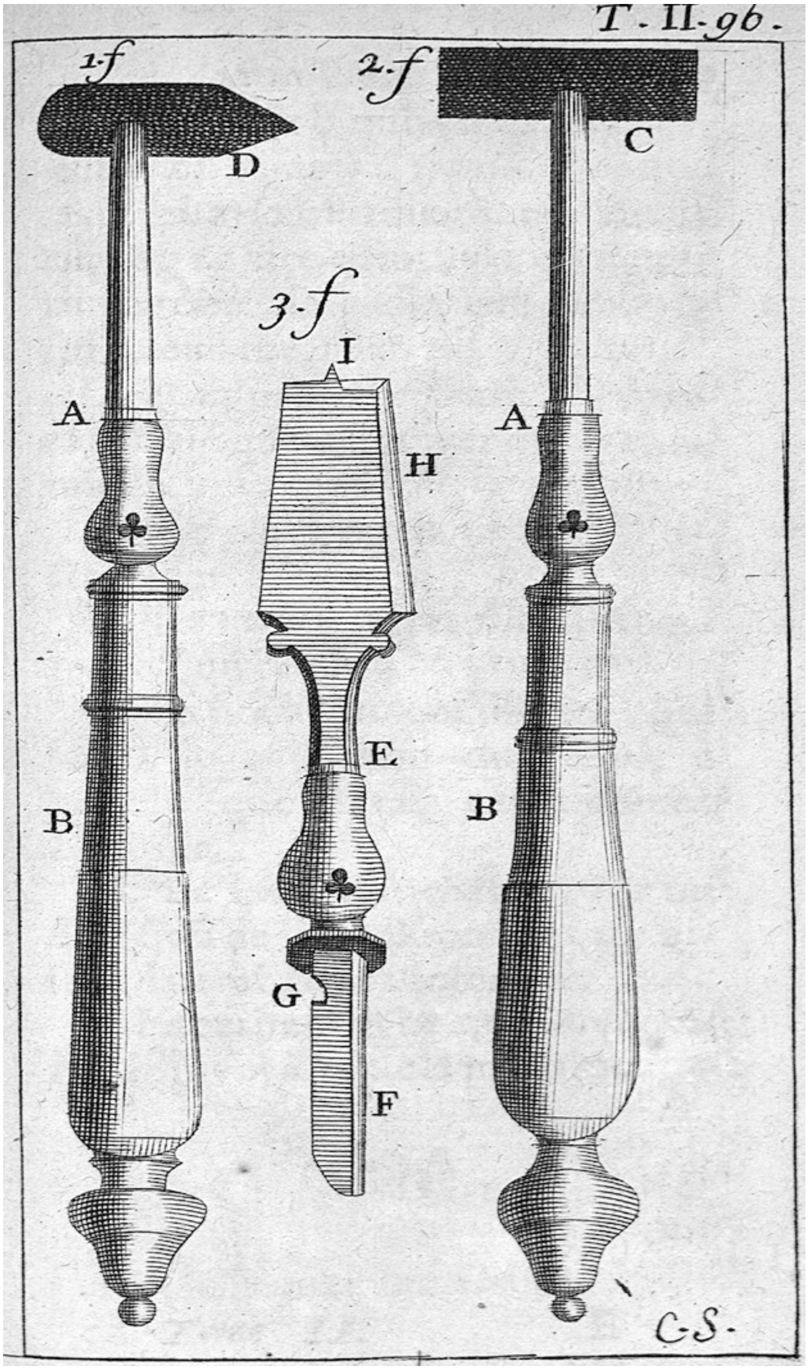
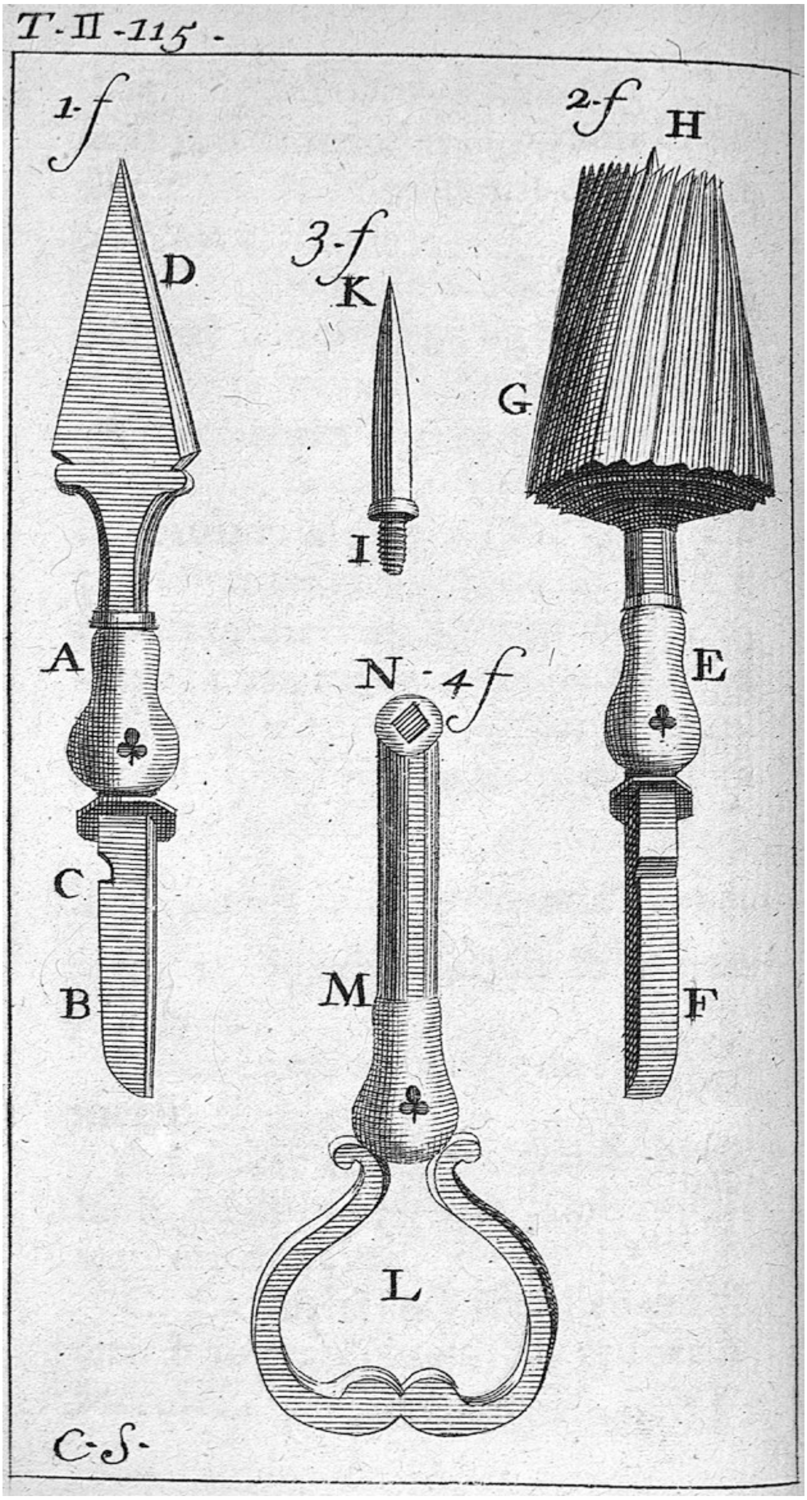


Fig. 16.5 (continued)



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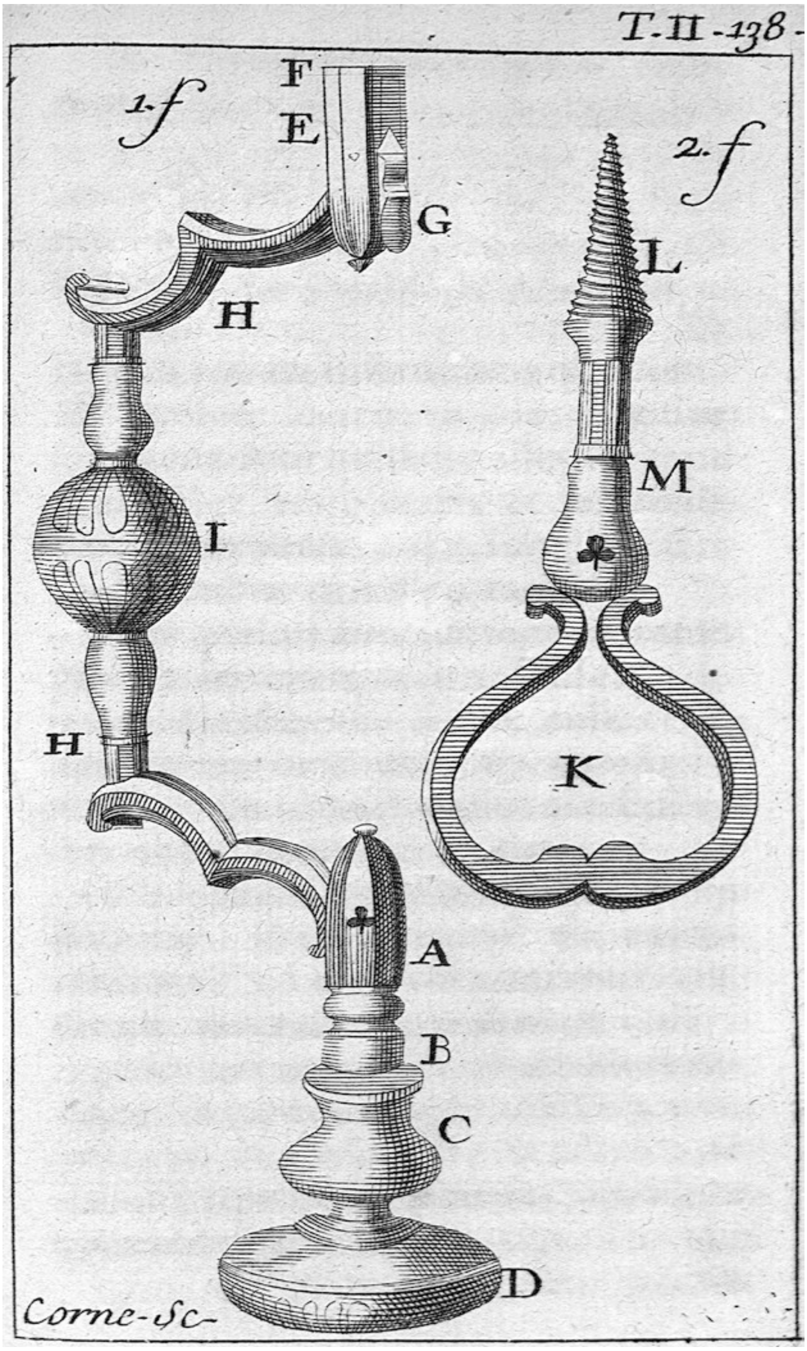

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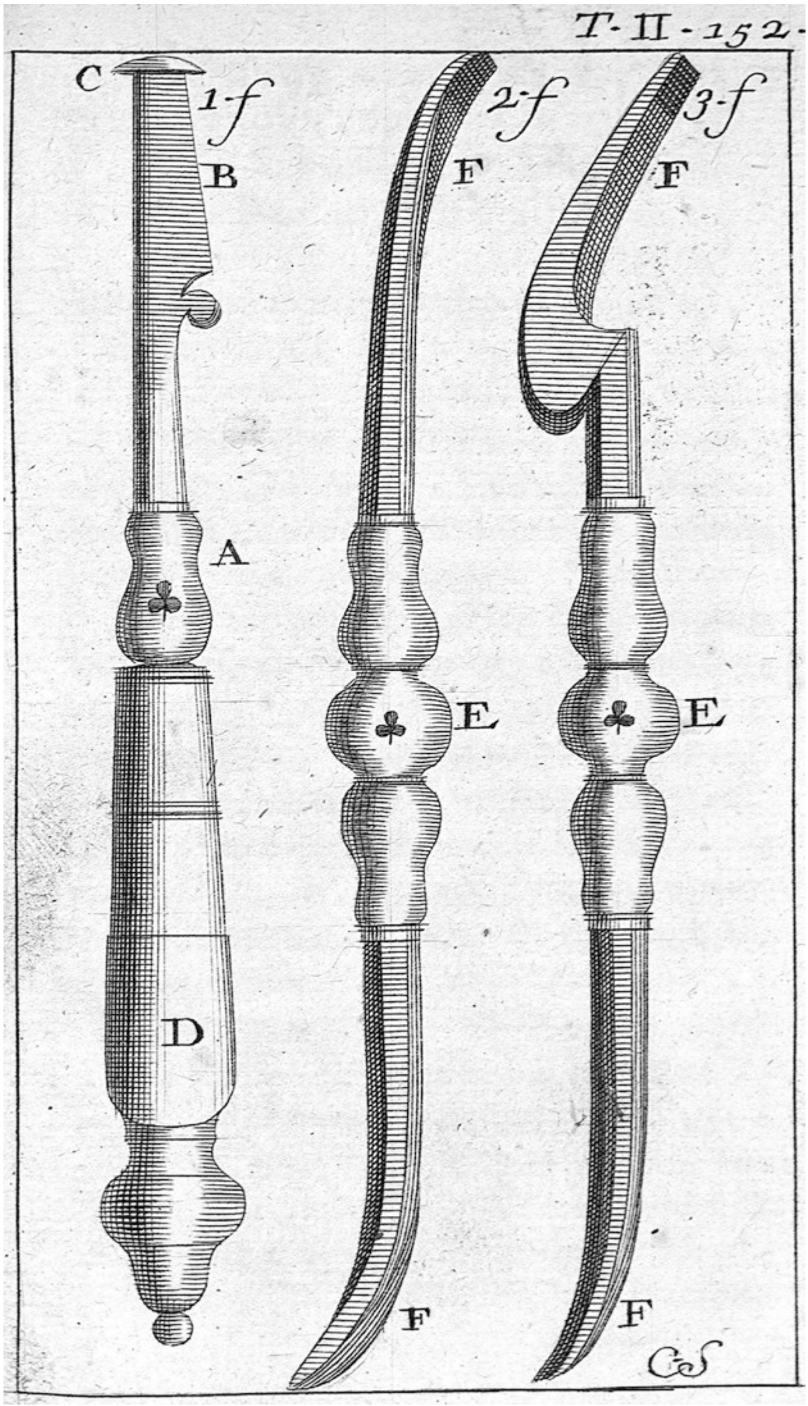

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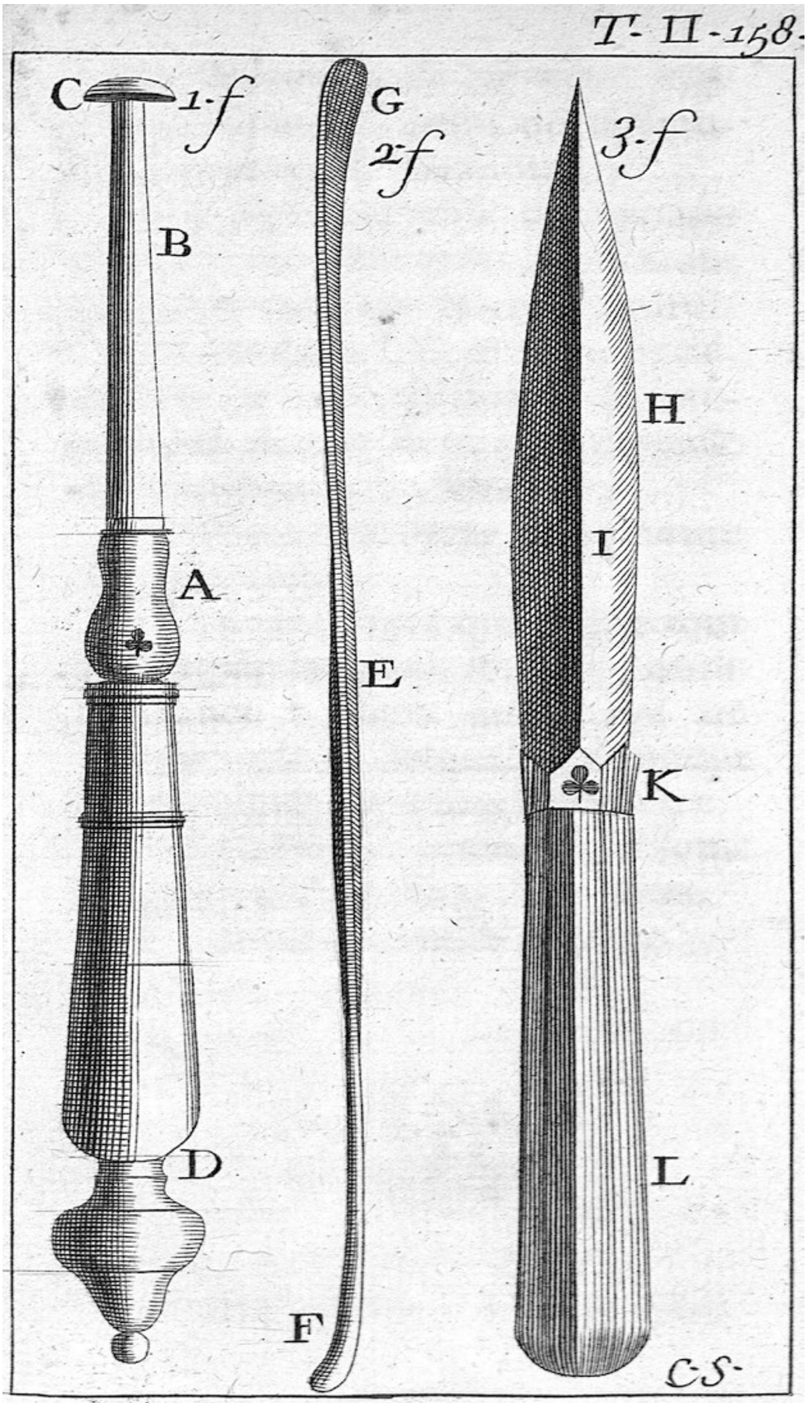


Fig. 16.5 (continued)

instrument with its widened end to be used simply as a depressor of the dura mater, the orifice of the trepanation, or to separate the dura of the bone at the edges thereof.

The French trepanation method using the brace and crown trephine was explained in detail in the most impressive scientific work of that time, which was not related to medicine in this case. It was *'L'Encyclopédie'* or in the *'Dictionnaire raisonné des sciences, des arts et des métiers'* which was edited in France between years 1751 and 1772 under the guidance of Denis Diderot and Jean le Rond d'Alembert [10]. The entries related with trepanation were written probably by Louis de Jaucourt (1704–1779) (Fig. 16.6).

The *'trépan'* is defined as follows: *'C'est une espece de vilebrequin de fer & d'acier, propre pour percer & scier en rond les os, principalement ceux du crâne. Il est composé de deux pieces, l'une est le vilebrequin ou le trépan proprement dit, l'autre est l'arbre sur lequel on le monte, & qui le soutient'* (It is a kind of crankshaft made of iron and steel, suitable for piercing and sawing round pieces of bones, mainly those of the skull. It is composed of two pieces, one is the proper crankshaft or trephine, the other is the hand on which it is mounted, and which supports it). The trepan is illustrated in plate XVI. There are three different types of trepan, 'l'exfoliatif, le perforatif and le couronné', which are meticulously described as well as are done with the shaft.

The crowned trepan has three parts. The middle and the superior do not differ in any way from the same parts of the exfoliative or perforative trepans. The crowned trephine is so called because its lower part represents a crown. It is a steel rod which supports a conical shape bowl, and which is bristling of sharp teeth which form a circular saw. Each tooth is at the end of a bevel, and all bevels are turned from right to left to cut in the same direction. They do not fall perpendicularly from the upper part of the crown to the lower one, but they descend obliquely and spirally, not only to better cut but also to chase away the sawdust. The crown is narrower by its extremity than by its breech, so that the piece of bone that can be sawed can easily be mounted as it advances. Its depth is about ten lines (*'1 ligne'* = 2256 mm); its width varies, because there are large, medium and small crowns. The diameter of the largest is from nine to ten lines in its depth, and from six to seven at its entrance, and the others diminish in proportion. In the bottom of the crown is mounted a pyramid, made as a punch, oval or square, terminated by its lower extremity in snake tongue, sharp, pointed, and a little longer than the crown. Its upper end is a screw with three lines of height. This pyramid is assembled and dismounted by means of a steel key. The pyramid is entered into the cavity of this key; we turn from left to right to mount it, and from right to left to remove it.

The book describes in the same detailed way all instruments for trepanation. These instruments are included in plate VXI (rugines, trepans, lenticular knife, lenticular and elevators) , and in plate XVII (elevators, strong bone forceps and cauteries). Plate XVII portrays the French surgical technique of trepanation. After describing the trepanation technique and instruments in a detailed way, the author discussed the indications and contraindications thereof. However, he mainly focused on giving recommendations about the doubtful cases. Among the cases where trepanation was allowed, the clearest options were skull fractures and depressions (*'De tous les signes qui peuvent déterminer à trépaner, il n'y en a point de plus décisifs que les fractures & les enfoncemens du crâne'*). A doubtful indication is a fracture where the bone fragments are so embedded that they do not allow the blood to come out and it accumulated over the dura mater. He also mentioned those fractures involving sutures, where blood could accumulate on both sides thereof as the dura mater adheres to sutures. In these cases, the surgeon had to trepan on both sides of the suture. Another embarrassing case were head blows with no apparent injury of the bone, sometimes without a wound or skin contusion. Effusions could accumulate under the skull

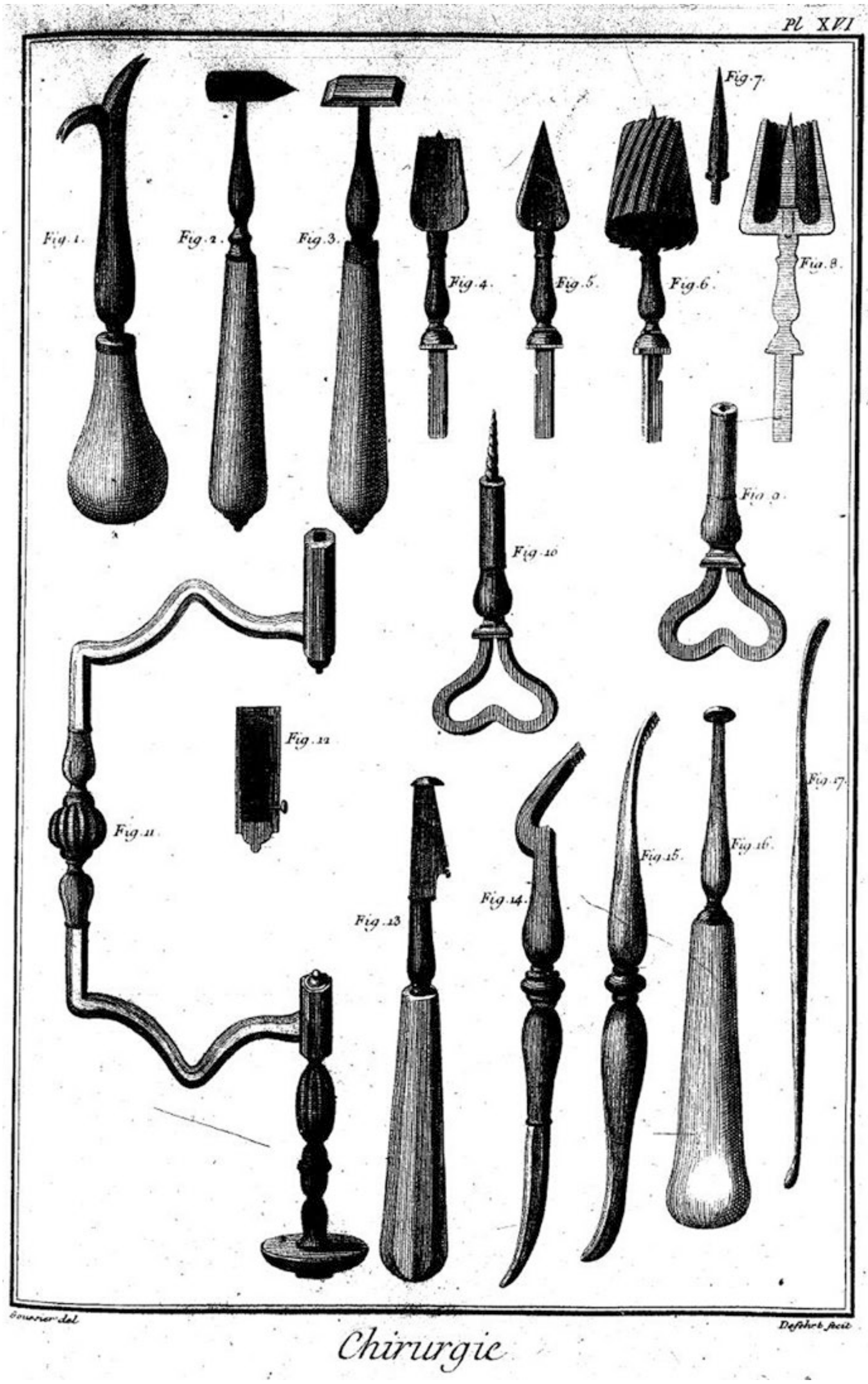


Fig. 16.6 Instruments related to trepanation that appear in L'Enciclopédie (Diderot D, D'Alambert R. L'Encyclopédie. Paris; Chez Briasson, David, le Beton, Durand: 1751–1772)

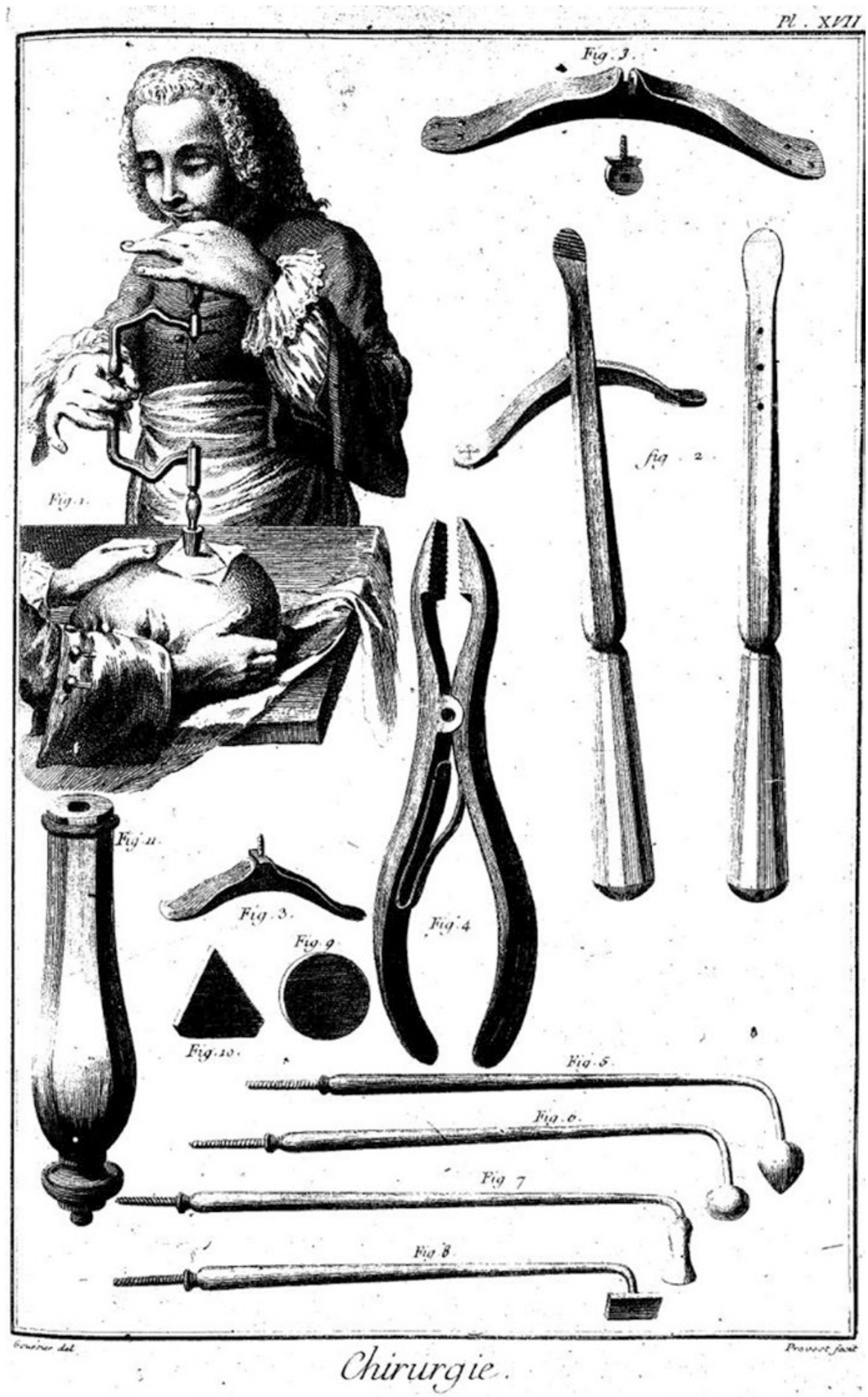


Fig. 16.6 (continued)

and the patient showed compressive symptoms. Some authors recommended trepanning whereas others suggested a treatment based on bloodlettings and other measures that avoided trepanation. On this regard, Quesnay's ideas were followed to distinguish between the primary and secondary complications. The surgical intervention with the trepan was more beneficial for the latter. Lastly, another doubtful indication of trepanation was those cases where the head wound had already healed but the patient had a continuous pain that instead of decreasing with time it became more and more intense in spite of all treatments. In this case the surgeon made incisions and exposed the bone. Some of them scrapped the bone (*'ruginer'*), whereas others used the exfoliating trepan and others suggested trepanning.

16.4 Other Less Radical Points of View About Trepanation

Lorenz Heister (1683–1758) was an example of a more eclectic point of view concerning the indication of trepanation in cases of head injury [11–13]. He was a renowned German scientist who was born in Frankfurt and later studied and worked in Germany and the Netherlands. Not only was he an anatomist and surgeon, but also an eminent botanist. He published *'Chirurgie'* in 1739. It was re-edited 15 times and translated into several languages. It was widely used in Europe in that time and in Japan sometime after, as it was exported by Dutch physicians. He also published *'Institutiones chirurgicae'* in Latin in 1749, which was soon translated into several languages such as English. He studied head wounds and traumatic cranial injuries in his main work *'Chirurgie'*. We have consulted an English edition thereof and must highlight a chapter that is expressly focused on cranial trepanation [12]. He only indicated trepanation for certain types of cranial fractures, as most of them were treated by lifting or removing the fragments. Trepanation was particularly interesting for blood extravasations between the bone and the dura mater, between the dura mater and the pia mater, under the pia mater or even inside the brain. He highlighted the importance of evacuating them by trepanation as *'the most fatal Symptoms, and Death itself, are avoided, by discharging the extravasated Blood through an Aperture made by this Instrument'*. In these cases (whose symptoms and signs were described in detail), the intervention had to be urgent (*'The less time you lose, the better'*) as delaying it could have fatal consequences for the patient. He recognised both the risks of trepanation and extravasated blood for the patient. For this reason, he concluded that it was impossible to determine a prognosis for a concrete case as *'most Patients miscarry after the Use of the Trepan, not from the Operation, but the violence of their Disorder, or the Injury received'*. The forbidden areas for trepanation were the classical ones suggested by Hippocrates; that is, the suture as the dura mater was very adhered to them, on the central part of the frontal bone, particularly on the anterior fontanelle or on the frontal paranasal sinuses and finally on the external occipital protuberance. Trepanation should not be carried out if a large artery or vein was found or if the bone was soft or had caries. Other areas that should not be trepanned were the lower areas of the skull covered by muscles, such as the occipital region, and the temples or temporal fossa. However, he recognised that it was possible when the muscles were detached.

Concerning the surgical technique Heister followed a very systematic protocol. He started the trepanation by shaving the area and making a cross-shape incision or an incision with an X, V or T shape. The incision was large enough to admit a trepan crown. He continued by denuding the bone. Haemostasis was achieved by means of a series of solutions that he describes. The trepanation was carried out some hours after, once the bleeding had stopped. However, the trepanation had to be carried out immediately if it was required. He then describes the drilling instrument. Although he mentioned the borehole used by ancient surgeons he pointed out that modern surgeons used the instrument with a brace handle and a truncated cone-shaped trephine drill (male and female) of different sizes that were interchangeable. The trepanation was started with a driller that made a small initial hole. He then used a male trephine and finally applied a female trephine. The brace head leaned on the chin or the forehead and the trephine was spun until it penetrated in the diploe and reached the internal table, obtaining a disc of bone. The bone sawdust was removed from the cutting crown with a brush. He recommended substituting the trephine by a lifter to lift the disc of bone during the final stage in order to protect the dura mater. The fragments of bone of the fracture were removed with the fingers or with forceps. A second or third trepanation was made when applicable until removing all foreign bodies from the dura mater or the brain. Once the dura mater was exposed, if the surgeon noticed it was taut or bluish it was a sign of blood or material accumulation underneath. He recommended making an incision with a lancet or scalpel, taking care not to injure the vessels. Once the trepanation was over, the wound was filled with gauzes soaked with topical medicines and it cicatrised by second intention. Once the definitive cicatrisation was achieved, Heister pointed out that it was not uncommon that patients suffered from headaches due to weather and temperature changes. He recommended then protecting the cranial defect with a silver sheet placed on the pericranium and fixed with an adornment. A tumour can also be formed in the cranial defect (brain herniation). It was treated with a compressive bandage or by applying pressure with a lead piece or by surgical resection when applicable.

Heister includes in his book two plates (plates 7 and 15) with figures of the surgical technique and instruments for trepanation.

Plate 7 contains trepanning instruments and the explanation is found in the text (Fig. 16.7a). Plate 7 includes an artificial eye made of glass or silver and painted, which can be introduced into the orbit to replace the lost natural organ and prevent the resulting deformity (Fig. 1). The trepanation instruments are as follows: Fig. 2: a punch to pierce the skull; Figs. 3, 4, 5 and 10: different types of *'rugines'* or scratching instruments to denude the skull or other bones; Fig. 6: in this figure it is demonstrated how the depression of the infantile skull can be solved. The text

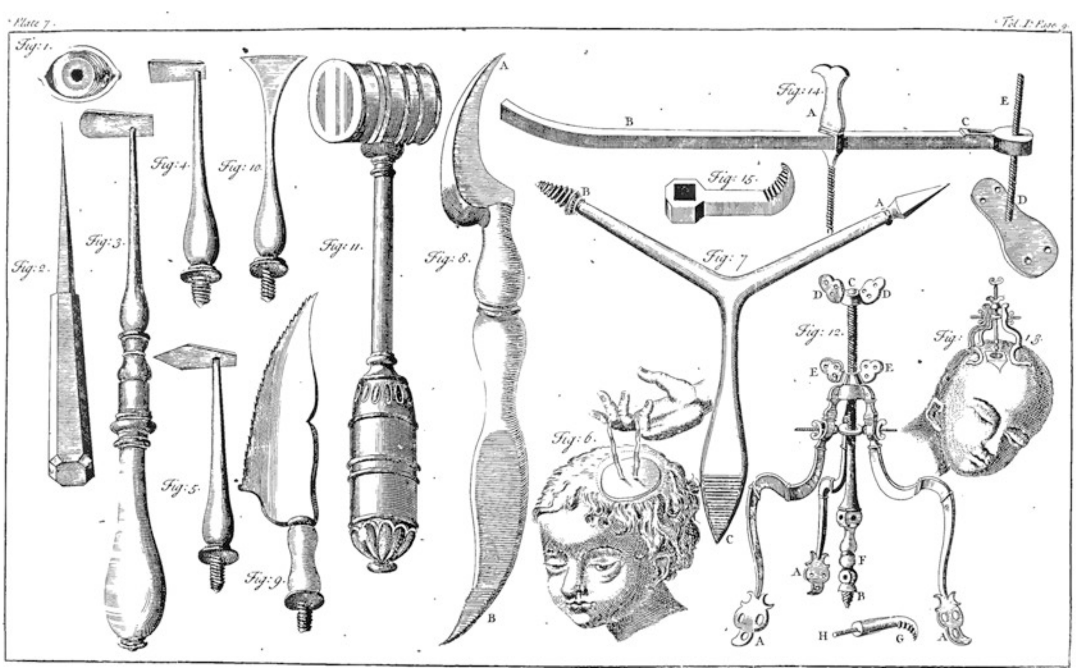


Fig. 16.7 Instruments related to trepanation by Lorenz Heister (Heister L. A general system of Surgery. London: W. Innys; 1745)

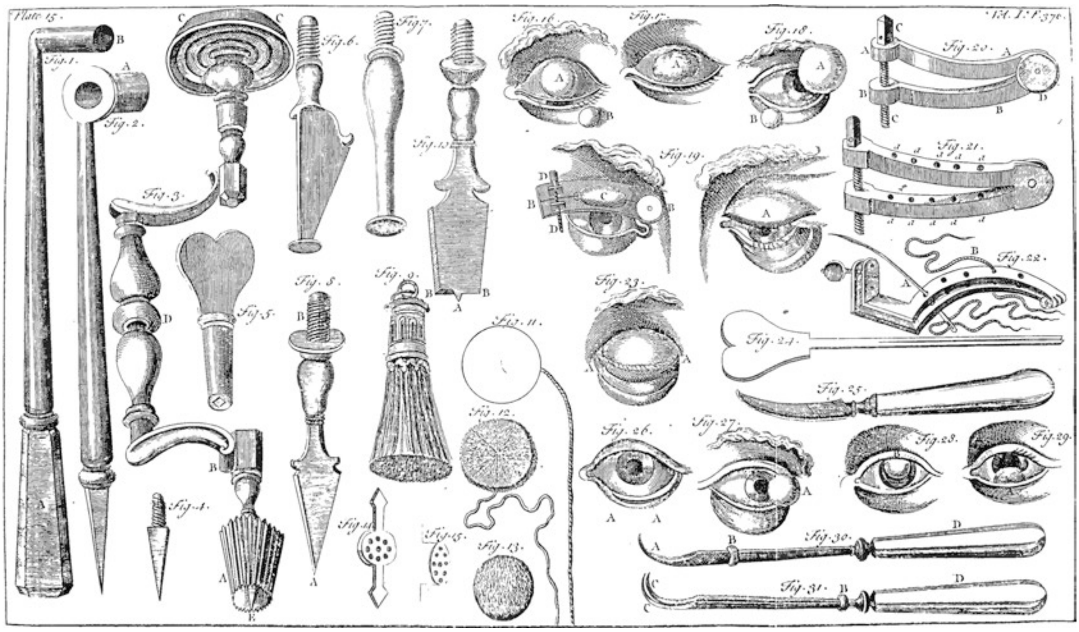


Fig. 16.7 (continued)

describes that a hot mould made of leather and covered in sticky and elastic material, which is allowed to cool down, is applied to the sunken fractures of children, to then pull the strings to raise fracture. It can be helped by closing the child's mouth and nose. If the elevation resists everything, the instrument of Fig. 7 is used; Fig. 7: instrument with a quadrangular tip to pierce the skull (A), drill (B) and elevator to lift depressed skull bones (C); Fig. 8: another elevator for the same use; Fig. 9: small saw that, like the *'rugines'*, can be used with or without the handle of Fig. 3; Fig. 11: wooden hammer, with the head filled with lead; Figs. 12 and 13: elevator with 3 ft., which Heister calls *'tripes'*, and how to use it; and Figs. 14 and 15: Hildanus's elevator with a hook for it.

Plate 15 contains many other instruments for ophthalmology and eyelids that occupy almost half of the page (Fig. 16.7b). The instruments related with trepanation and included in plate 15 are the following: Fig. 1: cautery to be used on the head; Fig. 2: cannula designed to receive and direct the cautery; Fig. 3: trepan that Heister uses (*'The trepan which I use'*), with the *'crown'* (A) and the place where it is screwed (B), the upper part of the handle (CC) where the hand pushes during the operation, the arc of the handle where the instrument is rotated (D) and the crown punch (E); Fig. 4: the punch of the extracted crown; Fig. 5: key thanks to which the punch is fastened and screwed into the crown; Fig. 6: lenticular scalpel (*'lenticular scalpel'*) with which the rough edge of the bone is smoothed after using the trephine; Fig. 7: steel instrument generally called a *'depressor'* with a button on one end to depress the dura and drain the underlying blood. Heister pointed out that his instrument is also called by some *'meningophylax'*; Fig. 8: a type of *'terebra'* to be coupled in the handle of the trephine (B) when the crown is removed and used to make the first entry for the punch of the trephine and also to drill the bone with the *'spina ventosa'*, so it is also sometimes called the piercing trepan, (A) points the tip and (B) the screw to be fixed on the handle; Fig. 9: brush to clean the teeth of the crown and trephine; Fig. 10: exfoliative trepan, which is sometimes used to scrape the rotten portion (*'carious'*) of the bone, with the tip (A) and the wings to scratch the bone when the instrument is turned; Figs. 11–13: different gauzes or surgical patties with or without rope for healing and filling the orifice of the trepanned skull; and, finally, Figs. 14 and 15: plumb line of belloste (mercury nitrate) to defend the opening and healing, and the way it should be bent.

Another surgeon who maintained an eclectic point of view was the Scottish author Benjamin Bell (1749–1806), who had the chance of working with Monro, Hunter or Pott. His master work was *'A system of Surgery'*, which was published in six volumes between 1783 and 1788 [14]. It was soon translated into French, German and Spanish and had several editions in the United States. This treatise included cranial trauma and explained the trepanation in a direct and clear way with no ambiguities. In the opinion of the author, this book was probably one of the most magnificent works of that time. Volume VI was made of many prints with the surgical instruments and their descriptions, although the rest of the work also includes some prints.

Benjamin Bell affirmed that the only important differentiation of cranial fractures was whether they were depressed fractures or not. He also distinguished brain contusion from brain compression. He admitted that trepanations should only be carried out in case of brain compression due to depressed fractures, blood, accumulations or pus which would be probably fatal if they were not solved. However, he warns about the trepan: *'it appears by no means an innocent remedy and is frequently of itself productive of dangerous symptoms'*. A second indication of trepanation was depressed fractures to remove or lift bone fragments. However, he preferred removing or lifting them without trepanning. Linear fractures should not be subjected to trepanation as they could spontaneously drain blood and fluids if they were separated. If not, they would only be trepanned if there was brain compression. In general terms, he rejected indiscriminate or preventive trepanation. Concerning depressed fractures in children he recommended lifting them with an adhesive mould stuck to the pericranium. If there was no wound or contusion external to the fracture it could be carried out with any of those symptoms or manoeuvres: pressing firmly the skull and observing if the patient moaned, moved the head away or moved the hand towards it, particularly if this response was repeated or if the patient repeatedly put his or her hand in a concrete area of his or her head.

Concerning the surgical technique, Bell pointed out that it was possible to trepan in any part of the skull, excepting for the dural venous sinuses, paranasal sinuses and the base of the skull. The surgeon made a cross or T-shaped incision or resected a circular or oval portion of pericranium of enough size to apply the trepan. He expressly said that the instrument to remove a piece of skull was called *'trephine'*, although he preferred the *'trepan'*, which takes half the time to drill the bone. According to Bell, the only difference between both instruments was the handle as he said: *'It (the trepan) differs from the trephine only in the handle being worked like a carpenter's wimble'*. The trepanation was started by drilling to insert the trephine pin. The serrated crown drilled the bone. It was repeatedly removed to check the depth of the perforation. The assistant cleaned the crown with a brush in those moments. The surgeon stopped trepanning after checking that the internal table had been drilled in one or two points. Then he used the lenticular and the lifters to finish cutting and lifting the disc of bone. According to Bell, the minimum size of the trepanation in an adult should not be lesser than an inch. All material, such as blood, serum or bone existing in the epidural space, was removed. He described the favourable evolution of patients, but also the dreaded brain herniation and its treatment. Once a piece of pericranium had been removed for the intervention he recommended placing there a brass or lead piece wrapped in flannel to protect the brain from the cold or other external aggressions.

In the volume IV of the book by Bell the traumatic problems of the head and the indications of the trepanation are studied, representing in plates VII, VIII, X and XI the necessary instruments, with the feet of figures in separate pages. These plates are reproduced in Fig. 16.8. In addition, in volume VI dedicated to descriptive plates of surgical instruments and techniques of all kinds, the same instruments appear grouped differently with the explanations of the figures also in text on

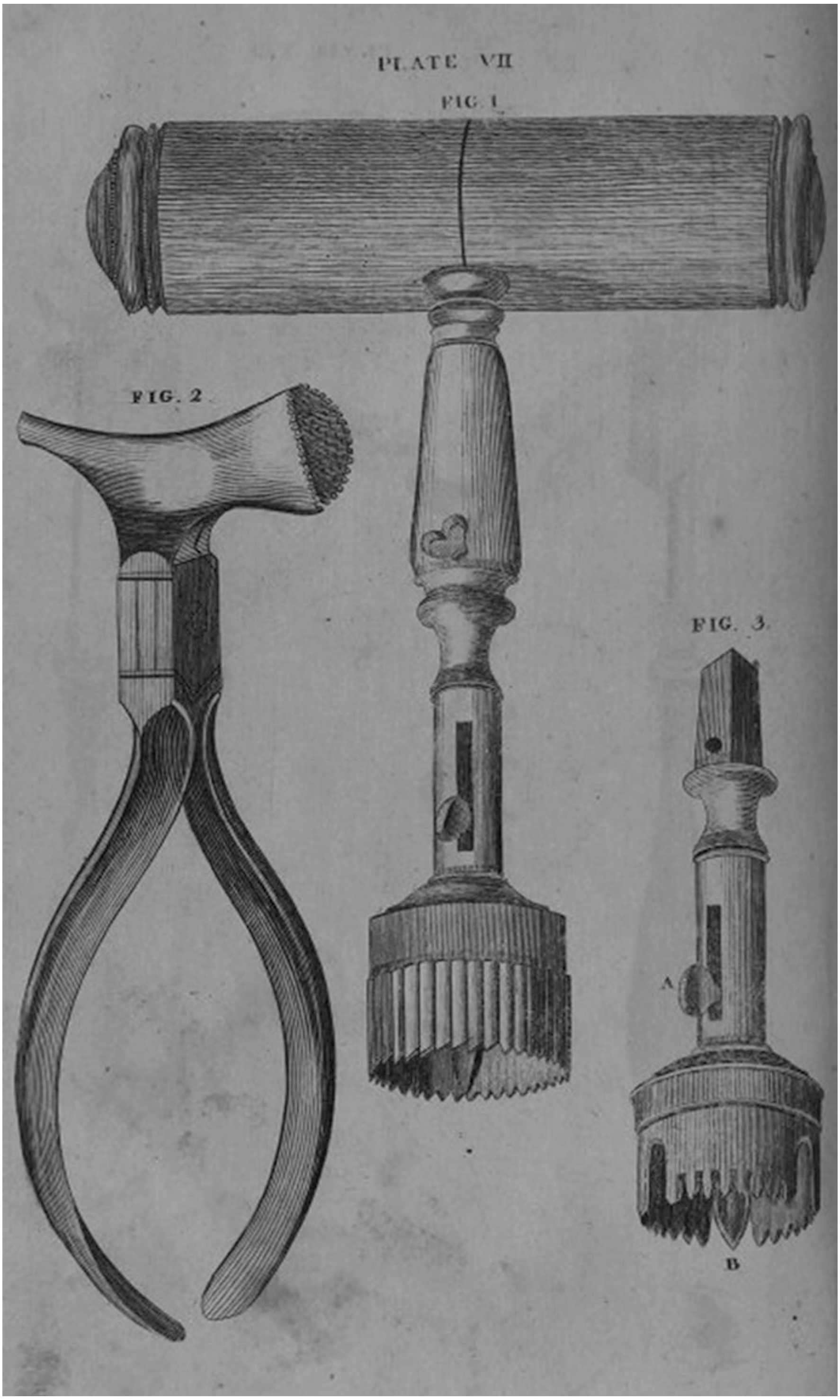
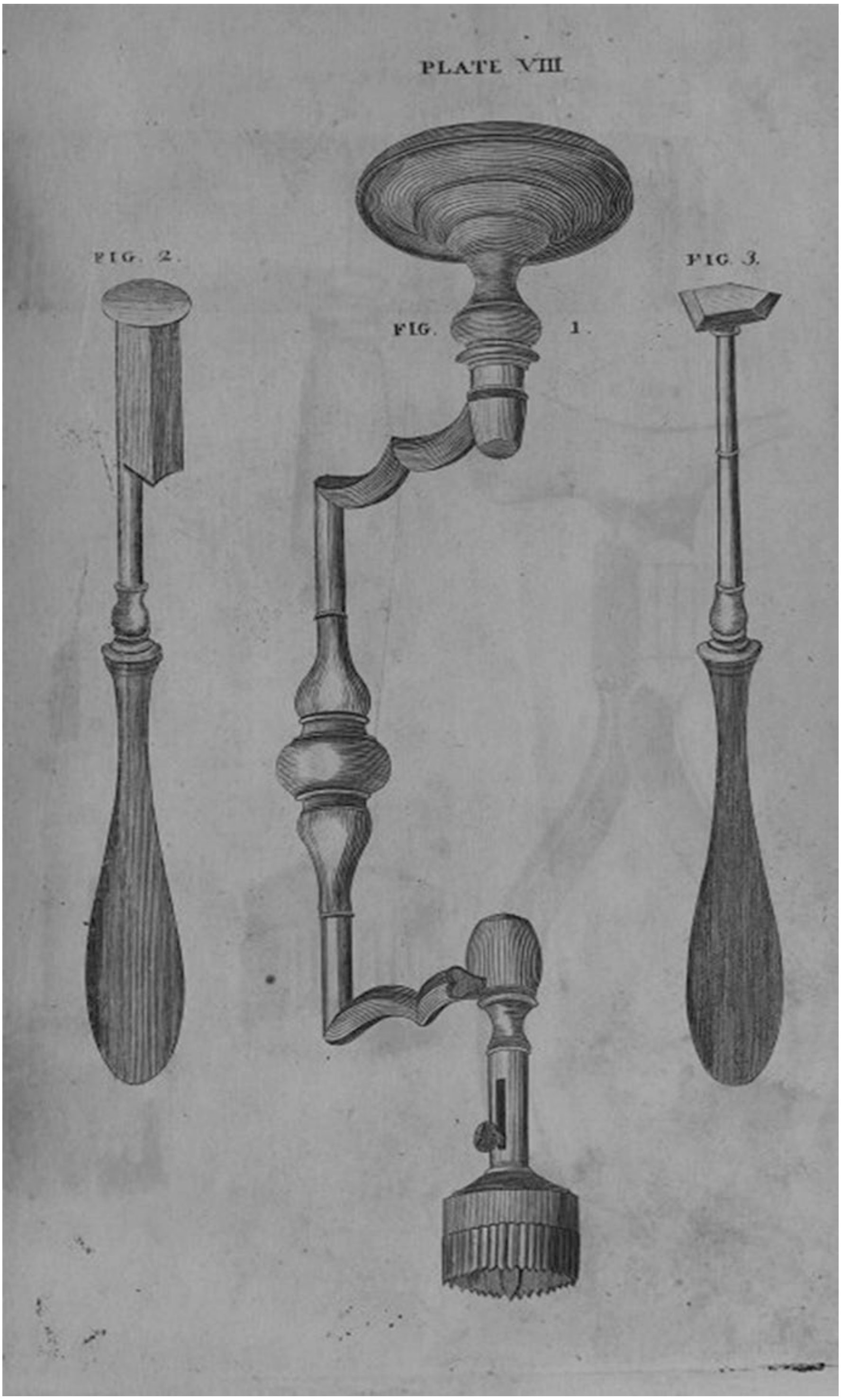


Fig. 16.8 Instruments related to trepanation by Benjamin Bell (Bell B. A system of surgery. New York: Penniman and Co; 1804)



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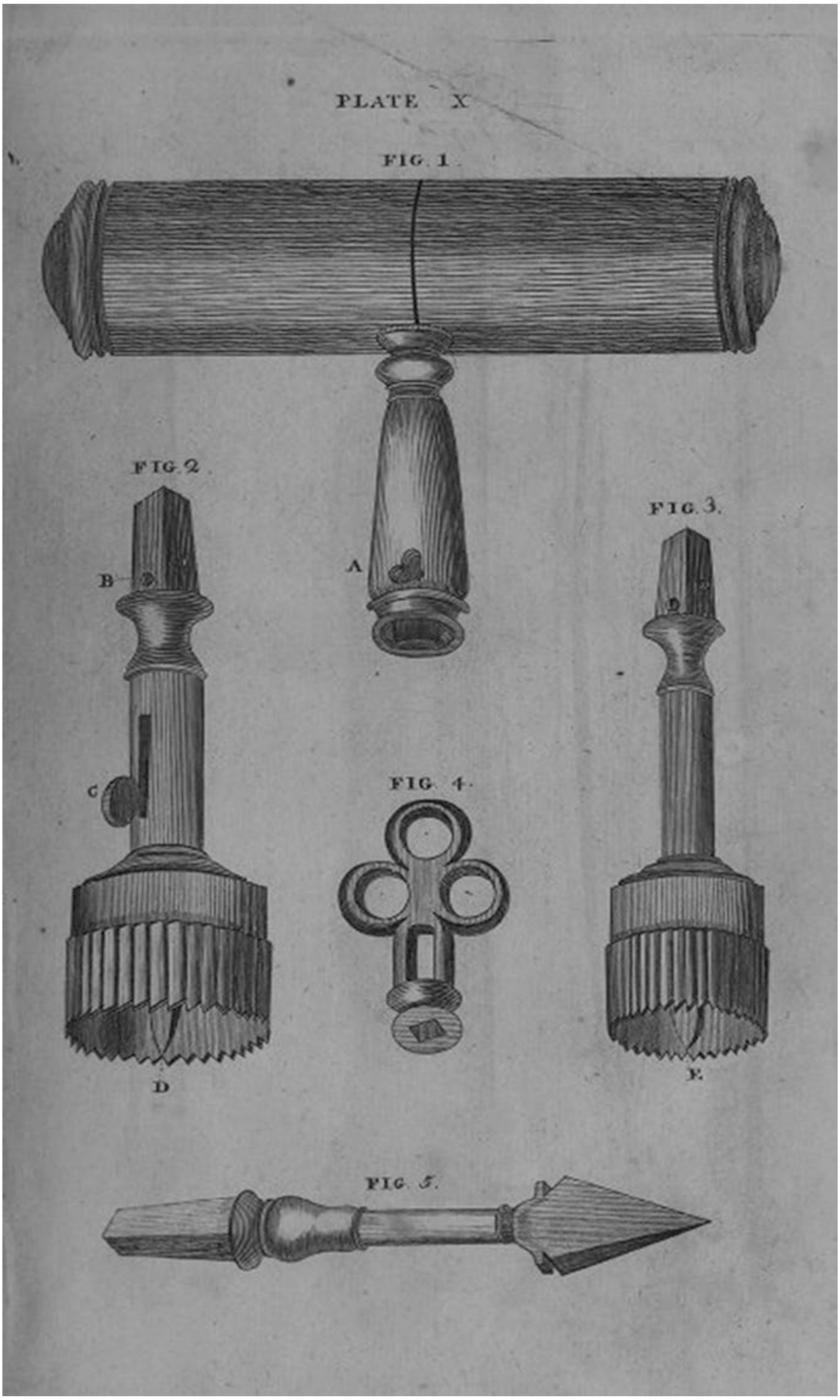

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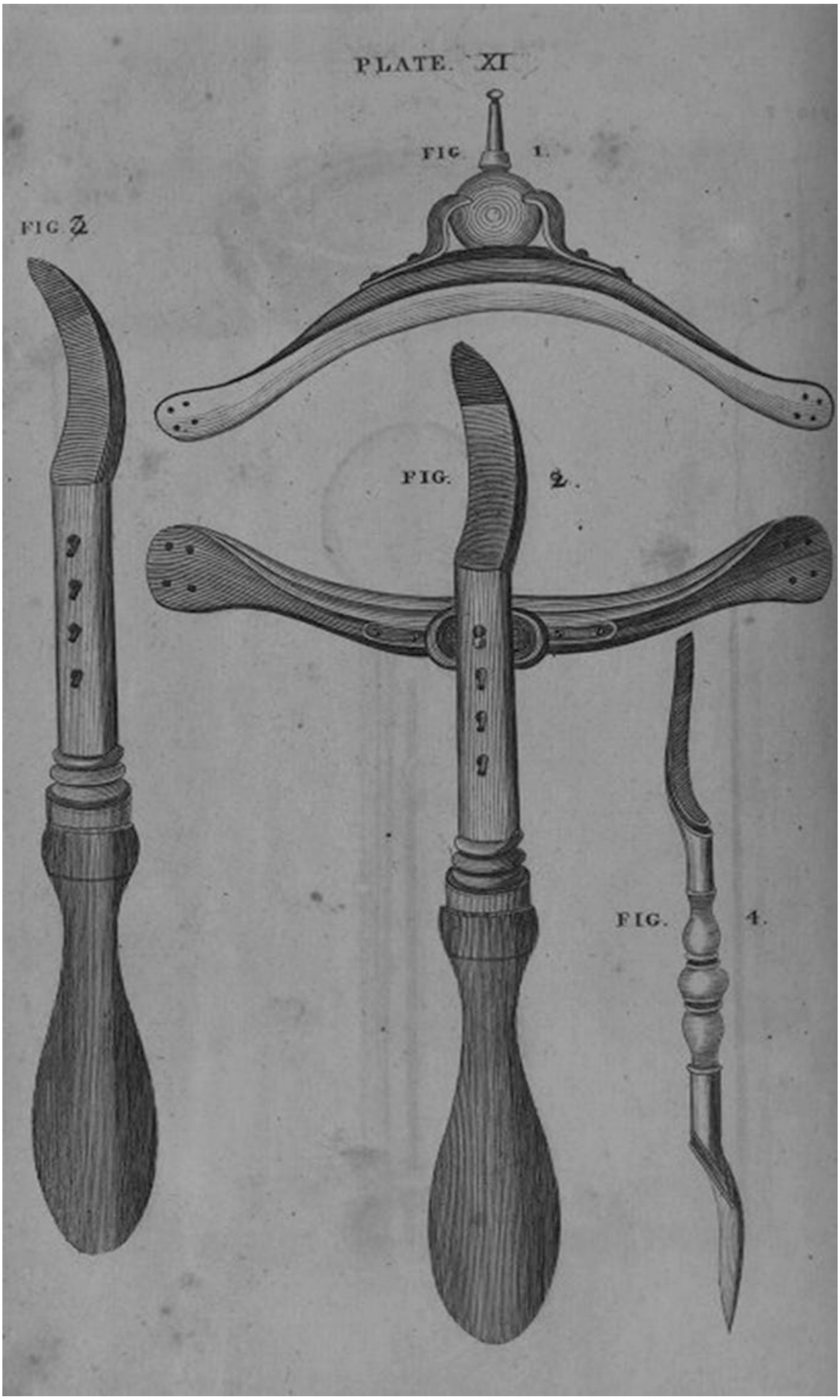

Fig. 16.8 (continued)

separate sheets. Therefore, we will only transcript the most relevant sentences of volume IV.

> *Plate VII. Fig. 1. A representation of the trephine of a full size for use. Fig. 2. Forceps for the purpose of removing detached portions of a fractured skull. They are also used to taking out pieces of the skull that have been separated or cut out by the trephine, when they do not come away in the head of the instrument. Fig. 3. A head of a trephine with larger teeth that the instrument in common use; and along the course of the saw, there are three vacuities in which the teeth are entirely wanting: by this is supposed that a piece of bone may be cut out more quickly than with the common trephine. … When the teeth of this saw are firm and properly set, it cuts both quickly and smoothly, but no better that instrument in common use.*

> *Plate VIII. Fig. 1. This figure represents the instrument, commonly named a trepan. As the page does not admit of the full size, every part of it is about one-third less than it ought to be. The upper part of the handle is of timber<, the rest should all be polished steel. For reasons that I have given in Chapter X. Vol. II. Every operator should be provided with this instrument as well as with the trephine. Fig. 2. This instrument is commonly termed a lenticular. It is used by some for scrapping the edges of the opening in the bone formed by the trepan, when they are found to be rough and unequal. … There is rarely, any cause for sing it: I have never found it necessarily…. Fig. 3. A raspatory for removing the pericranium before applying the trepan, but no more of the skull should ever be denuded than is merely necessary for the purpose.*

> *Plate X. The figures of this plate represent all the parts of the trephine separately. Fig. 1. The handle of the trephine, which should be made of timber. … Fig. 2. The saw or the head of the trephine: the upper part of it should fit with much exactness an opening in the under part of the handle, so that when inserted into the hole B may be opposite to the end pf the sewer A, when by turning the sewer A, the two parts of the instrument may be firmly connected together. C, the nut of a screw passing through a slit in the handle of the head, and fixed the upper part of a moveable pin, D. … All parts of the trephine are here also represented of a full size for use: the diameter of the saw should not be less than an inch. Fig. 3. A head of a small size as in the commonly used…. Fig. 5. A perforator for forming a small hole in the center of the piece of bone on which the head of the trephine is to be applied. … The perforator should be exactly fitted to the handle of the instrument, fig. 1. …'*

> *Plate XI. Figs. 1. and 3. Represent the different parts of a levator nearly the same with that Mr. Petit. … Fig. 2. The two parts of this instrument joined together, and ready for use. Fig. 4. Levator in common use; but this instrument, while it elevates one part of the skull, must press with so much force upon another, that it never ought to be used, especially as the elevator, fig. 2. Answers with perfect safety every purpose for which the other can be employed'.*

Therefore, the eighteenth century ended with a great controversy about whether 'to trepan or not to trepan' and supporters of both points of view. It was not resolved in favour of any of both sides; thus it continued throughout the first third of the nineteenth century. In that time, it seems that the challenges of trepanation were focused on improving the indications and the control of the infectious complications. This only happened at the end of the nineteenth century, when three milestones occurred: the adoption of antiseptic and aseptic techniques in surgery, the development of neurology by the recognition of the brain localisations along with their neurological topographical signs and symptoms and finally the development of local and general anaesthesia.

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17 Trepanation During the Nineteenth Century

According to Terrier and Péraire, three periods concerning the use of trepanation can be considered in the nineteenth century: an initial stage with a vivid discussion on the first third of the century, which led to an almost universal abandonment of the intervention during the middle third and finally a revival in the final third [1]. Nevertheless, at the end of the century, trepanation was definitively substituted by modern craniotomy.

There was a fierce discussion between those who were for and against trepanation during the first decades of the nineteenth century. It was nothing but the continuation of the controversy that originated in the eighteenth century we have discussed above. As an example of arguments for and against trepanation we want to expose the opinions of John Abernethy (1764–1831), born in London and contemporary of Benjamin Bell. He published several surgery treatises where he mentioned the trepanation. He was the author of the first publication about a neurosurgical topic in the United States, i.e. the book *'Surgical observations on injuries of the head; and on miscellaneous subjects'*, which was published in Philadelphia in 1811 [2]. He expressly said in his work that when some surgeons in France and Pott in England recommended the trephine in certain cases of cranial traumas *'they probably recommended a too free and frequent performance of that operation. Such appears to be the opinion of many respectable writers who have published since their time; particularly of M. Desault of Paris, Mr. Dease of Dublin, and Mr. John Bell of Edinburgh'*. However, according to Abernethy, the refusal to trepanning should not be extreme, as the arguments of the different authors were vague and futile (*'But although these writers unite in censuring the frequency of the practice, they are very far from being agreed in other respects'*). He highlighted two of the concerns that surgeons who recommended indiscriminate trepanning had. First, *'The older surgeons certainly trephined unnecessarily, in consequence of their belief, that the brain was an organ of so delicate a structure, that the least degree of pressure would be highly injurious'*. Secondly that *'Mr. Pott had an idea, that the bone would perish when the dura mater was detached for a considerable space from its inside'*. For these reasons, Abernethy described his observations on this issue, which were based on his personal experience from the St. Bartholomew's Hospital. Abernethy described a series of cases of head trauma treated with different practices. Some cases were treated without using a trephine, others were trephined and got worse and many others were solved with a trephine and by lifting the fragments. Some of them are particularly interesting, such as some cases of epidural haematomas caused by the rupture of the '*main artery of the meninx*', where he highlighted the lucid interval as a relevant clinical element for the clinical suspicion and the indication of trepanation. His

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clinical experience, which was gathered in his publications, was of 5 trepanations among 20 cases and a global mortality of 40%.

Be that as it may, the final result of these discussions and doubts was the rejection and almost abandonment of the intervention at the middle of the nineteenth century. The following information is an evidence of this situation. Malgaigne gathered the references about all trepanations carried out in France between years 1833 and 1841 with a total amount of just 15 cases which all led to the death of the patient. Only four trepanations carried out in France were gathered from the period between years 1857 and 1866. Nikolay Pirogoff (1810–1881), an eminent Russian surgeon, only carried out ten trepanations throughout his life. Finally, no trepanations were carried out at the St. Bartholomew's Hospital in London between years 1861 and 1867. Military surgeons almost never carried out trepanations in spite of the great amount of cases of cranial traumas they attended.

Many medical texts of that time were authentic diatribes against trepanation, with very radical points of view. Hence, the French surgeon Guillaume Dupuytren (1777–1835), who was very conservative, affirmed that trepanation was but a severe penetrating wound on the skull. Jean-Pierre Gama (1772–1861), a military French surgeon, was even more extreme about trepanation as he even wondered: *'Quel effect avantageux a-t-on pu obtener de ce procédé presque barbare?'*. Some surgeons, such as Johann Friedrich Diefenbach (1792–1847), radically changed their mind about trepanation during their professional career. He was in favour of trepanning all skull fractures at the beginning but he became one of the most active detractors thereof. Among his arguments against it he transcribed the feelings of a trepanned patient who remembered that he heard 'a terrible noise, as if I was under a bridge where a hundred thousand canons were crossing. It was so noisy I thought I was going mad …' while he was being trepanned.

Contrary to this point of view, other authors used probably the same arguments with a more favourable meaning. They considered that the trepanation was not dangerous by itself and that, although most head wounds and fractures could heal without requiring a preventive trepanation, it was true that once the complications appeared they were normally fatal in spite of the trepanation. For this reason, some authors argued that the bad outcomes of the trepanation depended mainly on the lack of accuracy of the indications and on the failures of the general treatment that the patient underwent. According to these and other reasonings, some German authors of the first half of the nineteenth century had a more favourable point of view towards trepanation. A review made by Schwartz in 1835 about 500 cranial trepanations pointed out that 330 of them were successful. He highlighted that among 133 cases which was immediately carried out 120 cases had a positive outcome. Another review made by Walther gathered 242 cases of non-trepanned cranial traumas, among which 159 led to the death of the patient.

The texts of that time, particularly the French ones, included long discussions against trepanation, answering particular questions about the convenience or not of trepanation in specific cases, such as wounds, fractures, complications or infections. Overall, the (individual or combined) elements that were considered in that time when deciding to indicate trepanation in cases of head trauma were the following: existence or lack of a wound; existence or lack of a fracture, and if so, the type of fracture, particularly depressed fractures; existence of foreign bodies; concussion symptoms; brain compression symptoms due to blood or pus effusions; and, finally, inflammation symptoms. Generally, they had reached a consensus on not indicating trepanation for wounds, non-depressed fractures and when there was a clinical diagnosis of concussion or inflammation. They accepted carrying out trepanations in those cases with certain types of depressed fractures, foreign bodies and clinical diagnosis of brain compression. Even when they accepted the trepanation there were some limitations, such as very deep foreign bodies which, just like effusions, were difficult to find. In any case, an element that caused a great concern was again the high mortality that the procedure involved, which was always above 50% of the cases. It was due to post-operative infections that as we said were initially attributed to exposing the dura mater or the brain to the contaminated air of hospitals.

In order to illustrate these points of view concerning the trepanation in that period of time we have chosen again a French surgeon, A.A.L.M. Velpeau. He introduced statistic arguments to suggest or reject the trepanation. We have also chosen an English surgeon, R.S. Hudson, who is a good example of the first self-criticism about the English point of view about the almost indiscriminate trepanation for any type of skull fracture.

Alfred-Armand-Louise-Marie Velpeau (1795–1867) was a French anatomist and surgeon who wrote a book about trepanation titled *'De l'opération du trépan dans les plaies de tête'* in 1834 [3]. He discussed the indications of trepanation for cranial trauma in his book. The book systematically analyses and criticises the areas of trepanation that were classically forbidden with the following conclusions: it is possible to trepan on sutures, it is very dangerous to trepan on the dural venous sinuses, frontal sinuses must be avoided, it is possible to trepan on the temples and the temporal region, if the surgeon trepans on the meningeal artery it must be cauterised and it is dangerous to trepan on the occipital region. Finally, he concluded that the only cranial area that must not be explored is the sellar and ethmoid region. The limit of surgery was the dura mater for Velpeau.

The most interesting aspect of the book is the analysis it makes about the trepanation in the different countries and schools of that time. It identifies inventories of those surgeons who were in favour and against trepanation. He was very critical with the British school that continued praising the almost indiscriminate trepanation for all cranial trauma. He reviewed the casuistry and outcomes of many surgeons, such as Dease and Pott, to support his arguments. Dease trepanned 11 patients who had no fracture, 9 of which died. He also trepanned 10 patients who had a skull fracture, 6 of which died. Velpeau ironically wrote that *'il perd la plupart de ses malades'*. Pott's series included 28 trepanations with 12 deaths. It showed better results and Velpeau attributed these outcomes to the fact that Pott operated immediately and that he carried out the trepanations on the adequate patients. Concerning the United States, he showed a discouraging situation of general science in that country (*'d'autant que l'Amérique n'a commencé à compter dans le monde scientifique, comme dans le monde politique'*). The same applied to trepanation *('nous ne trouvons presque rien sur le trépan dans les écrits publiés sur notre profession aux Etats-Unis'*). He described several interventions carried out and published there but he concluded that the observations were so few that no final conclusion could be drawn. However, he identified a general feeling in favour of trepanation. He then separated the supporters and retractors of trepanation in the German states and finally did the same with France. He also pointed out the point of view of his compatriots. Hence, he stated that the trepan intervention was useless for Desault, as he was emulating Bichat's ideas. On the contrary, Girault treated 30 cases of skull fracture and trepanned 6 patients, of which only 1 survived. Among the remaining 26 that did not undergo trepanation 18 died. He concluded that as the most severe cases were trepanned, the trepanation did not increase the severity of the patient's evolution.

It is interesting to observe that Velpeau made a rational analysis trying to match the mortality with several factors. It resembles some kind of modern multifactorial statistical analysis with the elements of that time. However, he concluded that when talking about trepanation we should not vaguely say that it has been used '*x times obtaining these results*' as there are other details that must necessarily be considered in the final prognosis: energy of the trauma, age and usual health condition of the patient, type of wound, concomitant diseases, hygienic measures and general treatment, among others. He reminded that if all patients were trepanned there would be a higher rate of survival but the trepanation could kill some patients that would survive if they were not trepanned. On the contrary, if only critical patients were trepanned the mortality would be the highest. However, it allowed to save patients that would die otherwise.

Robert S. Hudson was an English surgeon who worked in the mining region of Redruth in Cornwall (England). His paper *'On the use of the trephine in depressed fractures of the skull'* was published in the *British Medical Journal* in 1877 [4]. He vividly wrote about his first-hand experience concerning the situation of trepanation in the mining regions of England as a consequence of the adoption of Pott's ideas on this issue. He explained that before the use of helmets, many workers suffered from skull wounds and fractures in the British mines. The first question that the surgeon wondered for many generations when a miner came with a wound on his head was *'Is his skull broken?'*. If so, the next question was *'When are you going to bore'um?'*. For this reason, the surgeons of the copper mining town of Redruth carried out one or two trephines every week, some days even three. Trephinations were so frequent that it was quite usual to find someone who *'had been bored'* in any neighbourhood. For this reason, surgeons had collections of the resected discs of cranial bone at their offices that they showed to the sceptic people to prove the high frequency of this activity. As a general rule, patients walked back home, except those cases that were evidently critical. Hudson pointed out that this positive evolution was due to the early treatment of fractures. However, considering the current knowledge, it seems evident that many of the miners that were trepanned had no indications of any type of surgery. Another element that Hudson considered to explain the positive clinical results was the use of the trephine with a T-handle that was typical of English-speaking countries, instead of a brace trepan, which he described as a *'pointed trepan worked by a brace'*. It was still used in mainland Europe and, according to Hudson, it dipped easily in cranial fractures.

Hudson also thought about the relationship between the mortality rates by trephine and the indications and environment where the intervention was carried out. He pointed out that there was a high mortality rate at the hospitals contrary to the patients' homes, physicians' offices or rural environments, which had better results. The most shocking aspect of his analysis was the basic statistical review he made of the trephinations carried out at the Guy's Hospital in London, where the trephination was the surgical intervention with the highest mortality rate. It reached 76.6% among the 51 trephinations carried out between years 1861 and 1868, although these figures were similar to other London hospitals that he also reviewed. This high mortality was attributed to the septic atmosphere in which the surgeons had to work at the hospitals.

In addition to Hudson, there were already many surgeons who were against indiscriminate trepanation in the United Kingdom in that time. They generally admitted that trepanation allowed to obtain amazing results but the surgical intervention was complex and dangerous. In general terms, they admitted that it was useful for depressed cranial fractures. It was strongly recommended in those cases with compression symptoms that were supposedly due to an effusion, haematoma or pus accumulation. However, the difficulty to find the injury if there was no fracture and the possibility that the effusion was away from the fracture made the intervention risky. English surgeons opposed to trepanation in case of concussion and inflammation, as well as in case of wounds or simple cranial fractures.

If we consider it as a whole, the trepanation was almost repudiated in Europe by the second half of the nineteenth century. In fact, the surgeons looked for the suitable indications, since the surgical technique and tools for trepanation were consolidated and post-operatory infection could not be controlled. For that, a new interest in trepanation arose later thanks to the development of the aseptic and antiseptic techniques in first place. We can affirm indeed that the history of trepanation, just like general surgery, can be divided into two periods: before and after 1867, which was the year when the antiseptic system created by Joseph Lister was introduced. Trepanations were dangerous before 1867, but so was any type of surgery. The danger was in the hands of the surgeon, the instruments and the general conditions in which the intervention and the cleaning procedures were carried out. Suddenly, some interventions that had been forgotten, repudiated or criminalised such as trepanation were praised. Surgeons admitted that the trepanation was useful not only for head trauma but also for other non-traumatic brain conditions.

Lèon Gallez (1864–1898) made a statistical review of mortality rates of trepanation before and after the antiseptic techniques were routinely adopted in surgery in his book *'La trépanation du crâne'*, which was published in 1893 [5]. The author concluded with the following remark, which is also the last paragraph of his book: *'Sans attribuer aux statistiques une valeur qu'elles ne possèdent pas, on peut conclure que la trépanation a perdu beaucoup de sa gravité depuis l'antisepsie, et qu'actuellement elle n'entraîne pas une mortalité plus considérable que d'autres opérations de la pratique courante'* (Without attributing to statistics a value which they do not possess, we may conclude that trepanation has lost much of its severity since antisepsis, and that at present it does not cause a greater mortality than other current practiced operations). The review of the casuistry of trepanation in traumas before the antiseptic techniques showed a raw mortality rate that was above 50% in most of the series, which were, on the other side, pretty short. In an attempt to determine the risk attributable to trepanation, Gallez reviewed the series of cases that underwent a late trepanation due to non-severe conditions by themselves, such as epilepsy, where the mortality rate was reduced to 20–30% of the cases. The mortality rates decreased abruptly in all series and indications, with figures of less than 10%, after the antiseptic techniques were adopted. To be more stringent in his conclusions, Gallez suggested: '*Il serait extrêmement intéressant d'établir une statistique comparant les résultats fournis, dans un même ordre de cas, par le traitement chirurgical d'une part, par l'abstention opératoire d'autre part. Ce serait évidemment le meilleur moyen de juger de l'utilité de la trépanation. Malheureusement, les documents ne sont guère nombreux à ce sujet.*' (It would be extremely interesting to establish a statistic comparing the results provided, in the same order of cases, by surgical treatment on the one hand, and surgical abstention on the other. This would obviously be the best way to judge the usefulness of trepanation. Unfortunately, there are not many documents on this subject).

The second evolution that boosted cranial trepanation was the discovery of the brain localisation of neurological and mental functions, and thus the possibility to locate topographically the lesions by means of the clinical symptoms or data obtained during the neurological examination. This allowed to open the skull to remove the lesions by using cranioencephalic topography methods. These methods allowed to locate the relevant brain localisations by means of external cranial references. This way, the surgeon could reach the lesion through the cranial opening and remove it to alleviate the symptoms. This allowed the trepanation to move from the field of head trauma and solve a great range of non-traumatic cranial and intracranial pathologies that could be diagnosed and localised by the clinical manifestations and the neurological assessment.

The father of brain localisation was Paul Broca (1824–1880). Broca had the chance to study two patients with speech disorders in 1860. The first one was a 51-year-old man who was only able to repeatedly articulate a syllable (*'tan'*) when he tried to say something or answer any question. He was unable to construct any word or sentence. The autopsy showed a lesion of the left frontal lobe. The case was presented in the Society of Anthropology and in the Anatomical Society of Paris in 1861. They concluded that certain cognitive functions had specific localisations in particular gyri of the brain. Broca studied another patient of 84 years of age some months later. He had a 1-year history of minimum language production and only pronounced five words *('oui'*, *'non'*, *'tois'* instead of *'trois'*, *'toujours'* and *'Lelo'* instead of his name Lelong). The autopsy of the patient showed a lesion that was more or less in the same area than the previous patient. After these observations Broca concluded that the integrity of the third frontal gyrus seemed necessary to articulate words. This laid the foundations for functional localisations of the brain surface which allowed to make a clinical diagnosis of brain lesions of any type and their topography, apart from those related to trauma, which could be treated surgically.

Following this theory of cerebral locations, external cranial references were defined for the location of the most relevant anatomical structures (Sylvian fissure, Rolando's fissure or central sulcus, motor and sensorial cortical centres) and, what was new, the *'points de la voûte crânienne qui correspondent soit à des centres sensoriels ou sensitifs, soit aux centres psycho-moteurs de l'écorce cérébrale'* (Cranial vault points which correspond either to centres sensory or sensitive, either to the psycho-motor centres of the cerebral cortex). Few years after Broca's proposals, Victor Chalot (1850–1903) defines in 1886 the location of the typical points of trepanation for the cortical motor centres of the lower limb; of the upper limb; of the face and tongue; of articulated language; of aphasia or Broca; of the agraphia; of verbal deafness; of verbal blindness; of the hemianopsia or visual centre; and, finally, the centre of the conjugate deviation of the view [6, 7].

A historical figure that played an important role in both milestones (antiseptic techniques and localisation) was Just Lucas-Championnière (1843–1913). Lucas-Championnière was a French surgeon who travelled to Glasgow when he was still a student to know Lister's antiseptic methods. He was astonished and became a strong supporter of 'listerism'. He wrote the book '*Chirurgie antiseptique; principes, modes d'application et résultats du pansement de Lister'* in 1876 when he went back to France. He also invented a carbolic spray to be used in surgery. Lucas-Championnière also published many cases of trepanations that he carried out himself, as he was a strong supporter of this intervention. They were gathered in the *'Étude clinique sur 64 cas de trépanation du crâne'*. He thought that this intervention was not carried out enough. He became interested in prehistoric trepanation at the same time, which had just come to light and was reinterpreted by Paul Broca (1824–1880). Broca and Lucas-Championnière proposed localisation methods for a great amount of cortical structures of the brain, particularly sulci, gyri and fissures, by using external cranial references. Specifically, Lucas-Championnière wrote a book titled *'La trépanation guidée par les localisations cérébrales'* in 1878. It described the use of these techniques in cranial surgery [8].

As a consequence of all that, the trepanation overcame all obstacles at the end of the nineteenth century and physicians recognised again its usefulness in surgery. These changes were the precursors of the final flourishing of the trepanation at the end of the nineteenth century.

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18 Trepanation at War Times: Napoleonic Wars and North American Civil War

Trepanation had been carried out almost exclusively to treat head wounds and cranial fractures since ancient times. A large number of trepanned skulls of the pre-Columbian primitive cultures had skull fractures and injuries probably caused by weapons. The Hippocratic and Medieval texts make unequivocal reference to the treatment with trepanation of cranial and intracranial lesions produced by knives, swords, spears or projectiles used in battles. On the other hand, any type of head injury or cranial fracture described in ancient texts can be produced in combat by direct head trauma by sharp or blunt objects, falls, impact of heavy stuffs or hand-to-hand fighting [1, 2]. However, these injuries should not be very different from those that occurred in civil life or work activity.

Therefore, wars were a mine of cases and a source of experience for surgeons [3, 4]. According to Laín Entralgo, one of the relevant facts in the evolution of surgery between the Middle Ages and the Renaissance was the use of firearms in wars [5]. This also changed the type of wounds and it required a renovation of the treatment techniques that had been used until then, particularly those concerning head wounds and fractures and trepanation. In addition to the weapons, there were other changes in the period of time on which we are now going to focus, such as military tactics, number of soldiers involved and fight types. The disasters caused in the battles forced to design specific training systems for army surgeons and healthcare systems for injured soldiers. However, we only have reliable records of these aspects from the Napoleonic Wars that took place in Europe and the North of Africa and in the seas around the world. The information about the American Civil War is particularly rich and accurate.

John Fletcher Horne (1849–1941) described the evolution of the frequency of the trepanation in war head injuries. This evolution follows the general indications of the trepanation. In the latter part of the eighteenth century trepanation was widely employed, even as a preventive measure to avoid brain inflammation in every case of gunshot injury of the head, without sings of cerebral compression. Later, along the Peninsular Napoleonic Wars at the beginning of the nineteenth century, the number of trepanations declined. In the second half of the century, in the Italian War of 1859 or in the Franco-German War of 1870–1871, trepanation was exceptionally employed. Moreover, in every of these few cases, the results were unfavourable [6].

18.1 Trepanation in the Napoleonic Wars

The Napoleonic Wars devastated all mainland Europe between 1792 and 1815, causing millions of deaths and injuries. Most of the deaths were caused by infectious diseases, malnutrition or

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environmental consequences, particularly the cold weather. The most frequent causes for injuries in battles were low-speed projectiles that were shot by muskets, carbines and rifles as well as the shrapnel from grenades. The wounds made by sabres, bayonets and lances were less common.

In general terms, the medical services of the English and French armies were poorly supplied and organised. The English surgeons of that time started being trained at the age of 15 and worked as apprentices for 5–7 years accompanying their master. They learnt minor surgery, bloodlettings and bandages and helped the surgeon. They were granted the authorisation to work as a military or civil surgeon by an examining board of the College of Surgeons. Military surgeons quickly learnt their job at war and were subjected to a strong hierarchy. They were general surgeons and included among their tasks treating head wounds caused by projectiles and sabres as the helmets of that time offered no effective protection. Trepanations were carried out to treat cranial fractures and remove projectiles. However, they were not very frequent and many trepanation sets were never used. These instruments were sold by surgical instrument manufacturers in cases that contained all necessary material for surgery in the battlefield. The instrument case for trephination and amputation manufactured by J.C. Schenetter from Munich for the Imperial Russian Army during the first years of the nineteenth century contained 29 pieces. Among them, the following were aimed at trepanation: trepan with brace handle and three cylindrical trephine crowns of 5 cm, three Hey skull bone saws, a fragment lifter with a separate support to lever and lift the fragments, pincers for bone fragments, lenticular knife, lenticular separator for the dura mater, whale bone dissector to separate the dura mater and, finally, a brush [7].

The war ships also had surgeons who had been trained to carry out trepanations offshore [8]. To do so, among the crew of each vessel there was a surgeon with the necessary instruments. Due to the characteristics of the environment where they were used these instruments were subjected to strict controls. The Royal Navy Regulations of 1731 made it compulsory to keep the surgical instruments in a chest that was checked before shipping it and marked with the surgeon's seals and those from the Surgeons Company. No sea captain admitted it on board if both seals were not intact. This was done for two reasons, the first one to ensure that the necessary instruments were loaded on board and the second one to avoid selling the instruments due to their high price and the low salary of surgeons and barbers. The manufacturing companies sent the list of the instruments contained in the chests to the Surgeons College, who approved or modified it. The instruments were acquired in the Royal Navy and belonged to the surgeon himself or herself (Fig. 18.1). The chests had different sets for amputation, trephining, draining, dentistry, wound catheters and minor surgery, cupping and bloodlettings and also a mixture of assorted instruments and supplies. The trepanation set was made up of three trephine crowns with T-handle, a skull bone saw, periosteal elevators or *'rugines'*, a fragment lifter, a pair of forceps and a brush.

Among the military surgeons of both sides we must highlight Dominique-Jean Larrey in France and George James Guthrie in England. We are now going to describe their points of view concerning the trepanation in war wounded.

Dominique-Jean Larrey (1766–1842) was a surgeon in the Napoleonic armies and was involved in many campaigns throughout Europe and Egypt, including the invasion of Russia and retreat therefore. He was famous not only for his work as a physician but also for his achievements in the organisation of an early assistance in the battlefield as he designed an efficient system of ambulances and medical carriages ('flying ambulances'). Concerning trepanation, he affirmed that trepanning was essential in cranial wounds with depressed fractures or projectiles that might injure the dura mater or the brain or cause accumulation that might require to be drained. These comments are in his book *'Clinique Chirurgicale, exercée particulièrment dans les camps et les hôpitaux militaires depuis 1792 jusqu'en 1829'*, which was published in 1829 [9]. The brain compression was identified by the more or less extensive paralysis of different parts of the body that

Fig. 18.1 Photograph taken by the author that corresponds to a trepanation box dated at the end of the eighteenth century (National Maritime Museum Greenwich, London) and built with cloth, wood, leather and steel. The box contains a wooden T-handle with two different diameter trephine crowns and a perforator. There is also a scraper, as well as a horsehair brush with ivory handle. The box is completed by a lenticular knife and a lenticular dura mater depressor. Finally, there is a multipurpose clamp. The bone elevator is shown outside the box mounted on a support, but it has a slot in the box where it would normally be housed. This box contains the basic trepanation surgical instruments of British and American army surgeons

were in the opposite side to the wound. It appeared soon after the wound or gradually. It was not necessary to wait until these symptoms appeared to trepan in case the wound affected the frontal sinuses. Those projectiles embedded in the bone could be removed if the procedure was easy. However, if it was difficult it was preferable to leave them so that they would be expelled later naturally. He recommended exploring the path of the wound with an elastic rubber catheter. If the projectile was found it was removed through a counter-opening and by trepanning. He describes two illustrative cases. In case of a foreign body the burr hole had to be carried out so that the projectile was in the centre of the hole. If the projectile dipped in the brain substance the surgeon should not search for it. Larrey was aggressive with the wounds and projectiles that affected the frontal sinus and recommended trepanning. He described trepanations in the posterior fossa and lesions of the cerebellum. Curiously, he wrote a long chapter about the relationships between these lesions of the cerebellum and the sexual function. The optimal moment for the intervention was within the first 24 h, as the inflammation increased later. The book describes a great number of cases of injured soldiers, their injuries, treatment and clinical results. He repeatedly stressed the idea that the trepanation was useless when foreign bodies dipped in the brain and there were liquid accumulations extravasated away from the cranial vault as it was impossible to know where they were. He also considered unnecessary to trepan cranial wounds without foreign bodies, with non-depressed fractures or those that widely extended but had no brain compression signs. He talked about brain herniations through trepanation defects and their fatal prognosis in spite of the solutions used, such as surgical resection, compression with lead sheets or some methods of local treatment.

On the other hand, George James Guthrie (1785–1856) was a well-known English surgeon who served in the English armies during these wars, particularly in Spanish territories [10]. He published his *'Commentaries in the surgery of the war'* in 1815 and a monograph titled *'Injuries of the head affecting the brain'* in 1842, where he described his experiences. The indications of trepanation for war injured were depressed, open cranial fractures or bone fragments or shrapnel that eroded the brain, as well as those life-threatening brain compression situations that were due to supposed blood clots. The trepanation aimed to remove all bone fragments and the epidural blood to decompress the brain. The dura mater was the natural barrier of surgery and it was never opened, even the projectiles or bone fragments had invaded it. He only recommended the dural opening for those late cases, when a taut dura mater suggested a haematoma or empyema. The trepanation had to be carried out in the adequate moment, preferably soon. He was against late or last-resource trepanation. Although he was in favour of trepanation, he recognised his seriousness and stated that among ten healthy people trepanned at a civil hospital one died of the intervention itself whereas three or four would hardly escape from death due to the inflammation of the brain or the meninges or due to other problems.

18.2 Trepanation in the North American Civil War

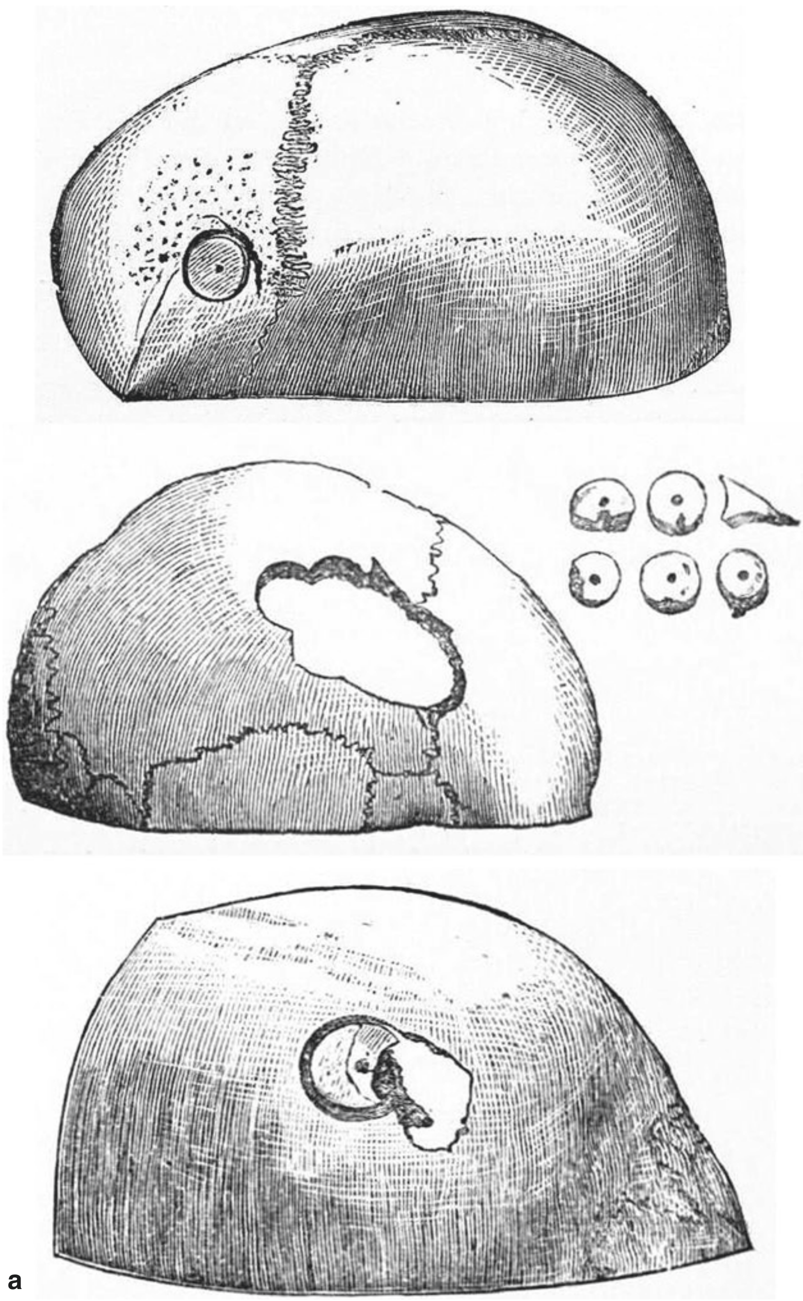
The Napoleonic Wars were the last ones with a massive use of soldiers and cavalry and where the wounds (regardless of their type and localisation) produced by sharp or cutting weapons were more frequent than those caused by firearms. In this conflict there were the first attempts to organise an effective and efficient military healthcare for the warring factions. The cause of war wounds changed later but the healthcare organisation was still poor and the new developments concerning the anaesthesia, aseptic and antiseptic techniques were not efficiently incorporated. During the Crimean War between the Russian Empire and France, the United Kingdom and the Ottoman Empire that took place between years 1853 and 1856 only the Russian and French armies had a minimal healthcare organisation. In spite of it, the mortality was incredibly high.

John Fletcher Horne (1849–1941) described in Chapter IV of his book *'Trephining'* the topic 'Trephining in gunshot wounds of the head' and reviewed the result of the operation in the different wars. Horne analyses the trepanation in the Crimean War. He says that the proportion of cases of trephining to gunshot head injuries in Crimean War was 3.11%, higher than in the American Civil War with a 2%. However, the recoveries were only 14.28% in the Crimean War compared with a 42.5% in the American Civil War. Horne does not find a clear explanation for this difference, only the much better knowledge of the cerebral localisation that allows the surgeons to apply the trephine more accurately according to the symptoms of the wounded. During the Crimean War the results were disappointing in every medical service of every Army involved in the war. A review of the casuistry showed that among 28 trepanned soldiers 24 died (86%). Only four trephined soldiers operated on by English surgeons survived and the results of the French surgeons were constantly unsuccessful. During this time it was suggested that the trephining could be only an additional complication to the original injury without any probable advantage. Therefore, some authors compared the results of the different types of treatment with the aim to isolate the trepanation as a risk factor. S.W. Goss found a crude mortality of 60.62% in 160 cases where trephine was used but 5.07% lesser when the fragments of the fractured skull were elevated or removed without boring the skull, that is, using elevators, saws or forceps. The conservative treatment had an ominous prognosis, with a success ratio of 25.26% of the cases.

The American Civil War or Secession War between the Northern and Southern States devastated the United States between years 1861 and 1865. It was probably the first conflict with a large amount of medical information.

The general situation of healthcare in the union and confederate armies was well described by Howard H. Kaufman, a neurosurgeon from West Virginia, in an interesting review of this topic that was published in the *Journal of Neurosurgery* [11]. Generally, both sides had a very poor caring capacity and the surgeons of both sides were not trained enough to attend cranial traumas and war wounds on the head. In addition to this, there was a lack of all kind of antiseptic measures and limitations in the availability of ether, chloroform or morphine. However, a great amount of the interventions were carried out with general anaesthesia. Military surgeons of both sides published manuals on surgical techniques. The surgeons had the trepanation kits described above. The result was a very high global mortality of 27.3% of those wounded in the Yankee side and of 37.3% in the Southern faction and 3.75% and 4.17% of those ill but not wounded in each side, respectively.

Soon after the American Civil War started the General Surgeon of the United States, Joseph K. Barnes (1817–1883), established some instructions to write detailed registers or medical and surgical records of the injured soldiers [12]. They included the information about not only the army of the United States but also soldiers of the confederate army, as well as about civilians who served the army. They separated the unionist white soldiers from the coloured ones. They also created a remarkable collection of relevant anatomical pieces from surgeries and necropsies (Fig. 18.2). The specimens were asked to regiment and hospital surgeons. The data about soldiers who were not attended by hospital doctors were not included, either due to the lack of importance of their wounds or because they had deserted or died before being attended. No files were opened in these cases. The General Surgeon Office used the data of this register soon after the war ended to create an amazing and detailed report entitled *'United States Army Surgeon General. The medical and surgical history of the war of the rebellion (1861–65)'* published in 1870. The report classified and described the type of injuries that were treated and had numerous summaries of clinical cases of each situation included in the classification. Part I of Volume II of such report included the information about head injuries in the chapter *'Wounds and injuries of the head'*. Head injuries were classified in three large groups: those mainly caused by sabres, bayonets and stabs, wounds of miscellaneous causes due to falls and blunt weapons, and last but not least wounds caused by firearms.



a

Fig. 18.2 Trepanned skull specimens belonging to soldiers of the American Civil War and collected in the Medical Army Museum. (**a**) Upper calvaria trephined in the left frontal region for gunshot contusion; centre: section of a cranium, exhibiting five trephine perforations for evacuation of pus, the result of a gunshot contusion of the right parietal; lower: segment of left parietal, from a patient trephined for depressed gunshot fracture. (**b**) Upper: section of a skull much shattered by gunshot, and trephined; centre: segment of skull trephined after fracture by a musket ball; lower: section of a skull trephined after a fracture by a shell fragment (US Army Surgeon General. The medical and surgical history of the war of the rebellion (1861–65) (Volume 2, Part 1). Washington: Government Printing Office; 1870)

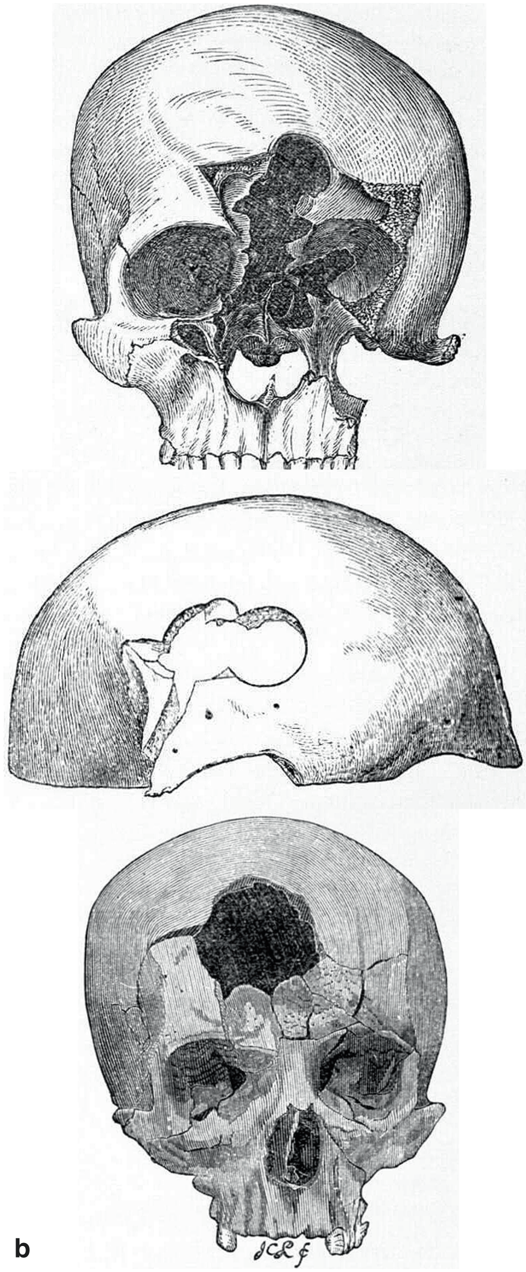


Fig. 18.2 (continued)

In the first chapter of stabbing and puncturing wounds caused by knives 282 soldiers with stabbing wounds on the pericranium were treated as well as 49 stabbing fractures of the skull. Among them, 5 surgical removals of the fragments and 3 trephinations were carried out, as well as 3 late revisions. It also included 18 puncturing wounds on the skull and finally 6 puncturing fractures of the skull. The report stated that the number of cranial wounds was undervalued as there were more wounds involving the head than those 21,444 stabbing wounds that were attended. The scarce number of puncturing wounds that pierced the skull was attributed to the type of weapons as the bayonets, lances and rapiers or swords were barely used. In any case, when they were used they aimed at the chest or abdomen of the contrary. However, cranial wounds of this type were fatal and all patients died, except one who became critically disabled.

A total amount of 508 cases were treated due to cranial traumas of different aetiology and made up the second chapter of injuries. It included injuries in soft tissues (with no mortality), injuries with brain affection but without a fracture (with a mortality of 19.4%) and injuries with skull fracture (with a mortality of 55.8%). We must also highlight that the classification system they used initially dichotomised to prove the existence or the absence of a cranial fracture. If there was no fracture, the next dichotomy was the existence or absence of brain affectation symptoms, which included neurological signs or symptoms of any type, either mild or severe. A total amount of 26 surgical interventions were carried out in this group of patients. They consisted of fragment removals and trephinations (18 patients) to treat depressed fractures. A total of 14 patients died (53.8%).

The largest group of patients included those with head wounds caused by a firearm, with a total amount of 7739 patients injured by bullets and shrapnel. They were mainly low-speed projectiles. Within this group, 162 deaths (2.09%) were not only due to the wound itself or complications thereof, including infection, haemorrhage, gangrene or tetanus, or complications derived from the treatment in three-quarters of the cases, but also due to breakthrough infectious systemic pathology such as typhus, malaria, dysentery or pneumonia. In the remaining quarter they were due to a mixture of other causes. Even if we admit the relative reliability of the administrative target data and the desertions, 552 soldiers were discharged with disability certificates and the remaining 7055 presumably returned to service (*'probably recovered'*). The general good prognosis can be attributed to the scarce energy of the projectiles that depleted in the soft tissues or bounced off the skull, which worked as an internal helmet in a war where the soldiers did not use any type of external cranial protection.

Among the 2493 cases of soldiers who were treated due to wounds on soft tissues caused by firearms there was a mortality of 4.4%. The primary treatment of the wounds on the pericranium consisted of washing, shaving the hair around the wound, removing foreign bodies, controlling the bleeding and protecting with a drape soaked in cold water. Most of the surgeons brought the margins of the wound closer with elastic bandages in such a way it was not too taut. A few of them used stitches when they aimed a primary wound closure. Otherwise they applied a drape or a waxed cotton gauze and did not bring the margins closer. Blind paths were rinsed with injections and washed to remove foreign bodies, particularly in the paranasal sinuses. They carried out counter-openings when applicable. When the wound swelled up (got infected) they used different treatments, from the simple wash to the use of emollient pastes, or applied drugs. Those wounds that had drained the pus were washed and kept open.

A more serious injury caused by the projectiles of firearms was the contusion of skull bones with bone excoriation but without evident cranial fracture. It generally had a good prognosis but there were cases of severe complications and with all kind of neurological symptoms. The mortality of the group was higher (55 of 328 patients, i.e. 16.8%) and 16 trephinations were carried out with a very high mortality of 14 patients (87.5%). The mean survival was only 3 days after the surgical intervention. Most of the deceased patients had intracranial pus accumulations in different places.

The next severity level in injuries would be the fractures of the outer table, including fractures of frontal and mastoid sinuses, with a total amount of 138 cases and 12 deaths (8.7%). 20 fractures of the internal table were described without a fracture of the outer table. They could only be diagnosed after the trepanation or the necropsy. All these patients except one died of infections. Four of them underwent trepanation without success. Linear fractures of both tables were described in 19 cases, 7 of which died (36.8%).

Most cranial injuries caused by firearms were different types of fractures of both tables. They included both simple linear fracture of both cranial tables and those cases with cranial fragments and projectiles lodged in the brain. The total amount of these injuries included 2911 cases of non-depressed cranial fractures with a mortality of 62.7%, 364 depressed fractures with a mortality of 35.4%, 486 penetrating cranial fractures with a mortality of 82.7%, 73 penetrating fractures with a mortality of 76.7% and finally 9 bursts with a mortality of 100%. A total amount of 385 cases underwent a surgical treatment to remove the skull fragments with a *'mortality rate of 37.6% only'*. Many patients also underwent trephination. Among 180 trephines carried out to treat cranial fractures caused by a firearm there were 96 deaths (53.3%). A 32.7% of those who underwent surgery survived with different degrees of disability. They were relieved of their duties and only four remained active in the Veteran Reserve Corps. Only 15 trephined soldiers (8.3%) were capable of resuming active service and other 6 were exchanged or judged.

Finally, 51 cases of brain herniation were described with a mortality of 86.3% in patients, many of which underwent fragment removal or trephination. Repairing the osseous defect was not considered in any case. They pointed out that, in those cases with a favourable prognosis, the cranial defect made by the trephine was filled at the end of the cicatrisation process with fibrous tissue and no bone callus was formed. Some physicians recommended protecting outwardly the osseous defect with metal sheets or leather discs. A suggested alternative to promote bone callus formation was to keep the denuded periosteum when the trephination was carried out and spread it over the dura mater.

Among those patients who were attended due to any of these injuries, 900 cases underwent surgery. Projectiles were removed in 175 cases (with a mortality of 48.3%), 33 vessel ligations were carried out due to haemorrhage (with a mortality of 36.3%), bone fragment removals or fracture lifting were carried out in 220 cases (with a mortality of 39%), 29 interventions were carried out to treat brain herniation (with a mortality of 75.8%), and finally 220 conventional trephinations were carried out (with a mortality of 56.6%).

The general principles of the indication of surgical treatment for war cranial fractures were the following. Primary treatment was justified for cranial wounds with cranial fractures with depressed fragments. In these cases, the fragments that compressed the brain were removed with a pair of strong forceps. A second indication was a wound with foreign bodies, such as tissue or projectiles, that had invaded the brain. In this case, if the fragments were found near the entry hole after carefully exploring the wound with a catheter they recommended removing them through the hole (which could also be enlarged). The third indication of primary surgery was in those cases without a wound on the skull but that showed brain compression symptoms, particularly if they were gradual. They considered that it would be very probable to find an epidural haematoma due to the rupture of the meningeal arteries. The drilling method used by military surgeons was the trephine with circular crown and T-handle with variable size and central pin. The trephine was applied once or several times in adjacent points or overlapping them until achieving a cranial opening with the appropriate size. The dura mater was still the most important anatomical barrier. However, many cases of removal of bone fragments and projectiles lodged in the brain were described. Some of them even survived. Many interventions were carried out at an intermediate stage of the patient's evolution before the wound had healed, particularly to debride the wounds, to treat complex injuries or due to the bad evolution. Finally, some interventions were carried out at a later stage, such as those for brain herniations.

Although written decades before, the book by Charles Bell (1774–1842) shows in some beautifully and dramatic pictures the most frequent traumatic injuries in war times [13]. The work is a publication with 19 plates on various surgical procedures, without text, of which the first four refer to instruments and technique of trepanation (Fig. 18.3). In *plate I* the trepanning instruments are represented: Fig. 1: Trephine of crown with handle in T and pyramid of adjustable length. Fig. 2: Hey's cranial bone saw. Fig. 3: Drilling tip. Fig. 4: Instrument, apparently to remove the

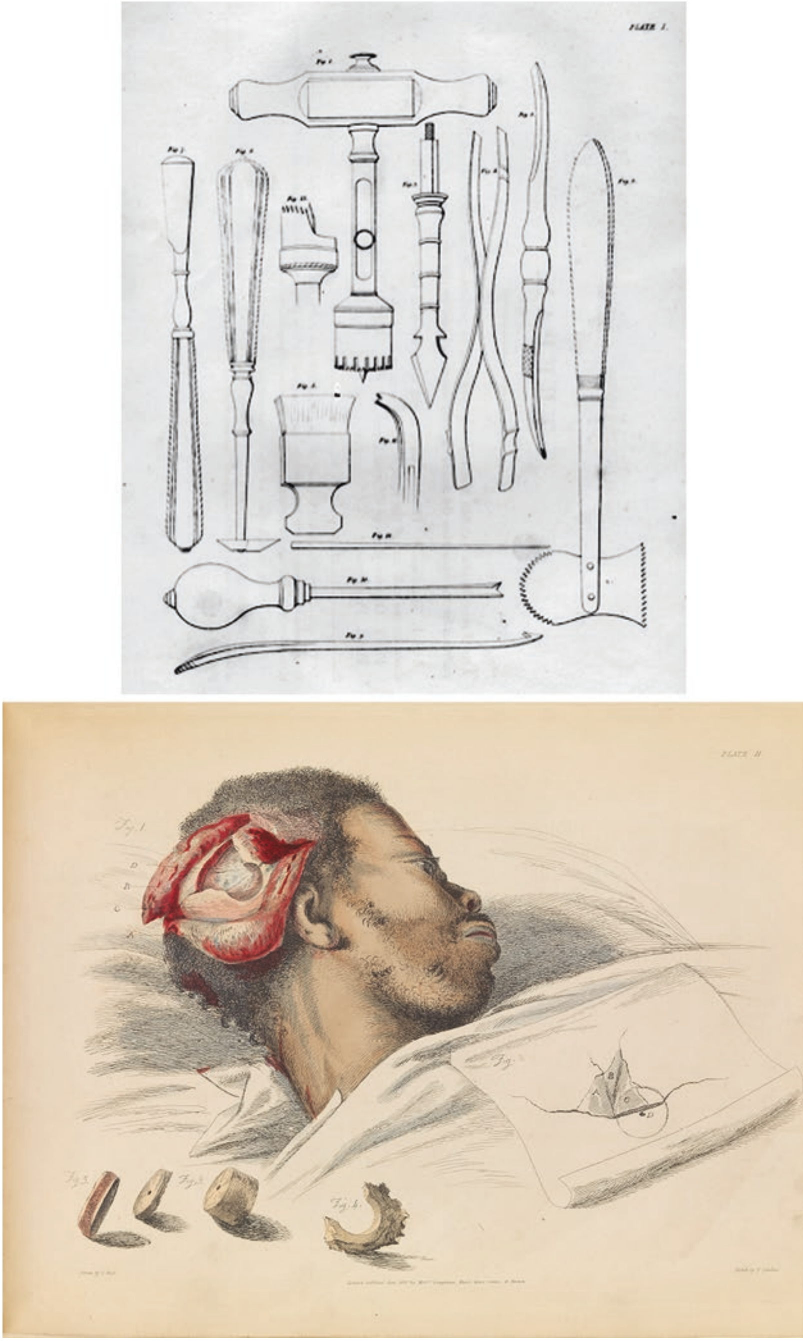


Fig. 18.3 Instruments for trephine by Charles Bell and some pictures with patients with head injuries (Bell C. Illustrations of the great operations of surgery. Trepan, hernia, amputation, aneurysm and lithotomy. London: Longman, Hurst, Rees, Orme and Brown; 1821)

Fig. 18.3 (continued)

bone disc. Fig. 5: Brush. Figs. 6–10: Different rugines, elevators and chisels. Fig. 11: Instrument, apparently pincer tip. Fig. 12: Probe. And finally Fig. 13: Partial-cut trephine crown. *Plate II* presents an African-looking patient undergoing trepanation, apparently in a case of trauma with a depressed fracture. The cranial wound has been enlarged in cross, the fragments have been removed and trepanation with a trephine crown has been practiced. The dura mater appears intact. Below are drawn several bone discs obtained after trephining and on a sheet of paper the fracture and the placement of the trephine are drawn, with the point of application of the central pin (D). *Plate III s*hows a dry skull with several fractures and trepanations. Finally, *plate IV* presents a patient with a moribund or perhaps dead appearance, with a frontal brain hernia after the removal of the fragments of a compound frontal fracture. The fragments of the bone are seen in the bed, next to bandages. The incision is surgical, with its typical cross shape.

The instruments for trepanation in war hospitals were stored in cases and their composition was regulated by the medical services of the armies. The trepanation sets started being manufactured in Europe at the beginning of the seventeenth century. They were exported worldwide and later they started being manufactured in the United States. The American Civil War triggered the mass production of instrument cases for general surgery, amputation and trepanation by the surgical instrument manufacturing companies in the United States, particularly those made by George Tiemann and Co. and Wade & Ford. The cases contained the instruments included in the lists that eminent surgeons had written for particular surgical interventions in the battlefield. The aim was to compile all instruments that would predictably be necessary for an urgent surgery in a single case and that such case would be compact and light enough to be easily carried from one place to another. The purpose of these kits, rather than containing all what could be found in hospitals or was used by regiment surgeons, was to forget the need of carrying several instrument cases when only a few are required.

The US Army and Navy ordered about 4900 surgical instrument sets for the Civil War to manufacturers placed in New York (Tiemann, Hernstein) or Philadelphia (Kolbe', Kern, Gemrig). Many others were confiscated, particularly 1150 trepanation cases. The surgeons hired for the war carried their own instrument sets at the beginning. A circular letter from the Surgeons General's Office described the composition of the instrument cases depending on the healthcare level in 1863. The instrument cases for major surgical interventions in hospitals included a truncated cone-shaped trephine and a small crown trephine, both mounted on T-handles. However, those sets for minor surgery or pocket cases did not include trephines. Field instrument cases of the regiment surgeons included a truncated cone-shaped trephine. The medical departments of the army of the confederate states used similar available cases and others that were imported from Europe after evading the naval blockade to which they were subjected.

18.3 Illustrative Cases

In this section we describe and discuss three cases of battlefield injuries treated with trepanation. The first two cases are patients operated on by Larrey and included in his book *'Clinique Chirurgicale, exercée particulièrment dans les camps et les hôpitaux militaires depuis 1792 jusqu'en 1829'*. He described them along with a series of cases to show the need of using the trepan for depressed cranial fractures with injury or depression of the dura mater (case I) and open cranial fractures (case VII), this case with a more complex clinical evolution.

The third case in one selected among the countless cases described in the book *'The medical and surgical history of the war of the rebellion (1861–65)'* was directed by the Surgeon General Barnes and published in 1870. This work includes thousands of cases. Some of them were briefly described and others were explained in detail. Some cases, such as the one we are presenting, included many details about the clinical evolution, the intervention carried out, the evolution and the findings of the necropsy. It is amazing that among those case reports we can find the one that starts as follows: *'CASE.—.L.—, aged 56 years, was shot in the head, at Washington, in the evening of April 14th, 1865, by a large round ball, from a Derringer pistol, in the hands of an assassin'*. The case corresponds to Abraham Lincoln (1809–1865), who was murdered on the 15th of April of 1865. He was shot at point-blank range on the occipital region. He died some hours later without undergoing any surgical treatment. A detailed report about his clinical evolution, treatment and necropsy is portrayed. It was included just like any other anonymous case among the thousands that were described in a more or less detailed way in the report. This proves the exhaustive data collection and the unaltered statistical processing of the information. The physicians involved in his treatment examined Lincoln's wound with a probe. Considering the patient's condition and the depth of the wound they decided to keep the wound open so that it spontaneously drained the blood. This was facilitated by manually cleaning the wound and removing some bone fragments with the fingers. The president was attended at a guest house in front of the theatre where he was shot. The autopsy showed that bullet was lodged very deep inside the brain, particularly in the frontal lobe near the corpus callosum.

18.3.1 Open Fracture Caused by a Firearm, Epidural Haematoma and Bone Fragment Removal

Larrey pointed out that the patient AP was a rifleman-grenadier who was shot on the right temporal region during the campaign in Austria. The patient showed *'les accidents de la commotion et de la compression'* at the same time. They were so severe that his life was at risk. Larrey debrided the wound, ligated the bleeding pericranial arteries, exposed the skull and found a fragment of the bullet that detached by itself. He lifted a large bone fragment with the lifter and felt that he was a lucky man after finding a second fragment of the bullet that was squashed between the dura mater and the skull. In that moment a great amount of black blood was spontaneously evacuated thanks to what he called a *'trépan accidentel'* and all the symptoms improved and gradually faded. The patient completely healed after 55 days. The scar was depressed and the brain pulsations could be noticed.

It was a case of open cranial fracture caused by the projectile of a low-speed firearm. It produced an acute epidural haematoma that caused loss of consciousness and focal neurological symptoms. The quick examination of the wound and the lifting of the fracture in search of the projectile fragments allowed an accidental evacuation of a non-suspected acute epidural haematoma. This saved the soldier's life. The line of action was flawless, considering the diagnostic possibilities of that time.

18.3.2 Open Fracture Caused by a Direct Trauma, Epidural Haematoma and Trepanation

Larrey presented the case of JB, a 32-year-old male who was a soldier of the first Swiss Regiment of the Royal Guard. He was attended the morning of the 22nd of January of 1826. His condition was critical when he arrived (*'fut apporté presque mort à l'hôpital de la garde'*) and he showed a blunt trauma on the left side of the head with a complex fracture of the skull and plunged fragments caused after falling or being hit with a blunt object. The detailed neurological examination was as follows: *'Ce militaire avait entièrement perdu l'usage des sens et de l'intellect; tout le côté droit était frappé de paralysie, et il y avait des mouvements fréquents et désordonnés aux deux membres correspondants à la blessure. La commissure des lèvres de ce côté était fortement tirée vers l'oreille; les pupilles étaient très-dilatées, privées de leurs mouvements; la lumière vive ne paraissait point faire la moindre impression sur l'organe de la vue, et le sujet ne pouvait proférer une seule parole. Le pouls, petit et traînant, donnait à peine quarante-cinq à quarante-six pulsations par minute; il y avait eu émission involontaire de l'urine, et effusion de sang par l'oreille du côté blessé: enfin tout annonçait une mort prochaine'* (This soldier had entirely lost the use of the senses and the intellect; the whole of the right side was paralyzed, and there were frequent and disoriented movements in both limbs corresponding to the wound. The commissure of the lips on this side was strongly drawn towards the ear; the pupils were very dilated, deprived of their movements; the bright light did not seem to make the slightest impression on the organ of sight, and the subject could not utter a single word. The pulse, small and trailing, gave scarcely 45–46 pulsations per minute; there had been involuntary emission of urine, and bloodshed from the ear of the wounded side; in the end everything announced a near death).

The surgical intervention was carried out immediately. After shaving the skull, a cross-shaped incision was made and the skull was denuded about an inch around the fracture. The pericranium and the *'muscle crotaphite'* (temporal muscle) were cut in a circular shape and removed until reaching the skull and ligating the bleeding arteries. As a lifter could not be used to lift the fragments a trephination (*'trépan'*) was carried out in the most declining area of the fracture. When they lifted the bone disc a lot of blood exited. They collected two ounces (1 ounce = 28.4 cc) of blood that was partially coagulated, evidencing the active bleeding of the meningeal artery. Once the epidural blood was drained, they observed that the dura mater was depressed and did not transmit the brain pulsations. Although they considered opening the dura mater they rejected doing it due to the serious complications that the procedure could involve. Therefore, they proceeded with coagulating by cauterisation of the bleeding meningeal points with an incandescent iron stylet. They applied the usual dressings, filling the osseous defect. A Galen's bandage was applied on the wound.

The patient improved right after the intervention was over as he started moving the right hand and emitting some words. The post-operative evolution was slow but the accepted medical treatment was constantly applied, from ice on the head to bloodlettings and repeatedly washing and cleaning the wound. The patient got out of bed 5 days after. 96 days after the accident and the surgical intervention the wound had completely cicatrised. It showed a central depression where the pulsations of the brain could be noticed.

It was a case of open cranial fracture caused by a direct trauma. It produced an acute epidural haematoma that caused loss of consciousness and focal neurological symptoms. He was a critical patient when he was brought to the hospital with a clinical situation that would correspond to a score of 5 in the Glasgow Coma Scale (eyes closed: 1, lack of verbal response: 1, uncoordinated spontaneous moves on the left side of the body: 3), which assesses the severity of the cranial trauma, ranked in this particular scale between 3 (the worst) and 15 points (normal). The patient showed dilated non-reactive pupils and a contralateral hemiplegia. Once again, Larrey's quick intervention and his trepanation allowed to evacuate an acute epidural haematoma that saved the soldier's life. The cause of the epidural haematoma due to the rupture of the meningeal artery and its treatment were described clearly and accurately. The line of action was flawless, considering the diagnostic possibilities of that time. The long evolution of the wounds was due to the fact that the surgeons preferred a cicatrisation by second intention, avoiding the primary wound closure. The circular resection of soft tissues fell within this category.

18.3.3 Wound Caused by a Firearm, Infection and Trepanation

Samuel Altman, a Private of the A company from the 50th Regiment of Georgia, was injured in the Battle of Antietam on the 17th of September of 1862 by a musket projectile. It left exposed about 2 in. long × about ¾ in. wide of the left frontal bone, with no bone depression or fracture. The patient was admitted at the hospital on the 27th of September. The wound quickly granulated and the patient had a very positive evolution, except for a personality disorder that was attributed to other causes. However, he started showing headache, fever and shivers on the 8th of October. The situation got worse 5 days later as he showed a quick but weak pulse, non-reactive natural pupils and loss of consciousness. The patient was suspected to have an abscess so he was anaesthetised with ether and the frontal bone was trepanned through the wound. The disc of bone was removed and the brain was punctured obtaining 6–7 ounces of a sero-purulent liquid with bone fragments. The liquid came out with so much pressure that it spurted reaching more than 3 ft (about a meter).

The patient improved in all aspects after evacuating the haematoma. His pulse and breathing were better and the wound was closed. However, the patient died that same day. The autopsy showed a necrosis of the internal table and caries of the frontal bone diploe. An abscess with indurated greenish walls was found in the anterior (frontal) lobe of the left-brain hemisphere. It had a diameter of 3 in. and was open to the ventricular system. There was no pus on the surface of the brain and no apparent continuity between the diseased bone and the brain.

This case shows the interest and fear that ancient surgeons had about linear cranial fractures, fractures of the outer table or cranial contusions as they might involve fatal complications. The evolution of this patient was what they aimed to solve scrapping the fracture, as we have previously discussed. It is obvious that the dramatic symptoms of the patient were due to the massive infection with osteitis, cerebral abscess and ventriculitis that could not be solved with the trepanation. The frontal osteitis can be explained by the direct wound infection due to contamination. However, the lack of communication between the osseous infection and the frontal abscess does not exclude retrograde contamination through a thrombophlebitis. An abscess that opens to the ventricular system is today an extremely life-threatening situation, even with an external ventricular drain and systemic or intraventricular antibiotic therapy.

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19 The Question of the High Mortality of Trepanation and Trephine

Along the eighteenth and nineteenth centuries an important aspect on the discussion about 'to trepan or not to trepan' was the incredibly high mortality associated with trepanation. Nowadays it is very difficult to analyse the causes of mortality and the factors involved due to the lack of reliable clinical and epidemiological information. However, one of the underlying factors that has been always considered as an essential reason for this high mortality of trepanation during this time was the infection. It was associated with the putrid air of hospitals in that time. Before the pathogenic agents were discovered, the theory that infectious diseases were spread by the 'unhealthy air', also known as 'miasma', was accepted. The Hungarian physician Ignác Semmelweiss (1818–1865) broke this myth as he proved (in a pretty unsuccessful way in that time) that puerperal fevers were caused by the doctors themselves who attended the delivering women and transmitted them after staying working in the dissection rooms with corpses of women infected. Just like other surgeons who observed that the mortality of trepanations was higher at hospitals than in other places, Semmelweiss noticed that the mortality caused by the puerperal fever was higher in those deliveries at the hospital than outside the hospital environment. Additionally, at the hospital, the mortality was higher in those rooms where the delivering women were attended by physicians. Semmelweiss suggested that physicians should wash their hands, first with soap and then with calcium hypochlorite, before attending and examining delivering women. This simple measure dropped the mortality and started the era of the asepsis.

This relationship between hospital mortality and infection by direct contamination in surgery has been a true act of faith along decades but there were some other alternative interpretations. Jeremy C. Ganz recently studied the problem of the infection in trepanation during the eighteenth century [1]. He reviewed the literature of that time on this topic and gave an unconventional hypothesis. This study also allows to get an idea about the practice and experience that the authors of that time had on trepanation. Ganz gathered 14 papers and texts about the results of trepanation. Twelve of them were English and two were French but translated into English. Only seven of all these texts had enough data about the topic and could be analysed. The case load of the authors was between 14 and 71 trepanations, with a global mortality between 16.7% and 57.1%. The mortality due to infection was between 5.6% and 54.1% and the mortality among those infected was between 33.3% and 100% of the cases.

The first factor Ganz discussed was the source of the infection. Concerning those series that included wounds and where patients were operated early, it would be logic to think that the infection came from the initial contamination of the wound itself or by the surgeon's actions. On the contrary, in those cases in which they operated

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close traumas the infection surely came from the surgical intervention or dressing. As there were no clear differences between both groups and many patients underwent an early surgery and had wounds, the factor involving the surgery, hospital and cleaning procedures could not be adequately assessed as a cause of the infection. However, according to the author, it would be less important than the one initially supposed. When they analysed those cases treated at hospitals against those treated in other places they noticed that the global mortality and the probability of lethal infection did not increase.

When considering the cities where surgery was done, they clearly observed that those surgeons who operated in small towns had a lesser amount of infections and a lower mortality than those surgeons who worked in big towns. Ganz concluded that, although there is no reliable information on this topic, we had to admit that the general hygiene conditions in surgical practice would be as bad as in any other place as there was no preventive measure on this respect in any place. However, the general health conditions of people living in rural environments and small towns were better than in big towns, which conferred them better opportunities against infections. One of the series studied by Ganz was the one that James Hill (1703–1776) published. He trepanned 8 of his 18 patients and had a global mortality of only 16.7% of his patients. Hill worked in Dumfries (Scotland), which had a population of less than 5000 people in that time. It was well known for its 'clean air'. The other series that supported these conclusions was the one published by Sylvester O'Hallaran (1728–1807), who trepanned 25 of his 71 patients and had a global mortality of 29.5%. He worked in Limerick, an Irish town of about 10,000 inhabitants in that time. The relationship between the trepanation, infection and mortality will be later analysed again in the second half of the nineteenth century, right before the antiseptic and aseptic techniques were widely adopted in hospitals.

In front of this, Dublin had about 150,000 inhabitants and between 600,000 and 700,000 inhabitants were living in Paris or London in the eighteenth century. In both cases, the sanitary and hygiene conditions were terrible and the life expectancy was less than 40 years. At that time Percivall Pott (1713–1788) reported a mortality of 51.1% among the patients submitted to trepanation in London and Henri François Le Dran (1685–1770) reported in France a mortality as high as 57.1%.

Later, in the nineteenth century, the indications of trepanations were more restricted in patients with head injuries, but the mortality persisted with very high figures, which was always above 50% of the cases. In a review done by WD Foster about the *'Results of trephining'* done in 1883, the author states that the operation of trephining in civil practice *'has been followed by varying results in the hands of different surgeons'*, although *'the operation finds undoubtedly its greatest success in private practice'*. He says also that *'in military practice the results of trephining for fracture of the skull with depression are extremely disastrous'* although *'In our late war* (American Civil War) *the trephine was applied, it would appear, with much greater frequency, and with vastly more gratifying results'*. Foster reviews the result of trephining for '*all causes in 220 cases'*, with the following results: 95 recoveries, 124 deaths and 1 undetermined, with a mortality ratio of 56.6%. And finally, Foster concludes that *'trephining the cranium should be regarded as an operation always fraught with danger, and only to be performed from absolute necessity'*.

This high mortality was attributed to postoperative infection. The selected strategy by surgeons to fight against this high mortality was looking for most accurate indications for the cranial opening, but the results were disappointing. Robert S. Hudson reviewed the mortality of trepanned patients at the end of the nineteenth century in England in his paper *'On the use of the trephine in depressed fractures of the skull'* [2]. He reports a mortality of 76.6% in the Guy's

Hospital of London between years 1861 and 1868. As decades before, these figures were much more favourable in his series of patients operated on in the patients' homes, physicians' offices or out of the hospitals.

It seems that the challenges to reduce the post-operative mortality of trepanation were focused in the eighteenth and nineteenth centuries on improving the indications and the control of the infectious complications. This only happened at the end of the nineteenth century, thanks to the adoption of antiseptic and aseptic techniques in surgery. The terrible high mortality was reduced and the cranial opening surgery was reintroduced into the surgical armamentarium of that time at the end of the nineteenth century.

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20 Evolution of the Surgical Technique of the Trepanation and Trephine in Modern Age

Although it can be stated that the evolution of the instruments, techniques and indications of the cranial opening was not very fruitful between the sixteenth and nineteenth centuries, it seems logical to accept that there was a slow process of continuous improvement in all aspects. During all these centuries, the most relevant improvement was that a series of taboos and restraints in the cranial surgery were demolished. These changes are discussed in this chapter, but before that we describe the 'state of the art' of trepanation in the seventeenth and eighteenth centuries through the description of the technique in the surgical texts of the time

20.1 Surgical Technique of Trepanation in the Seventeenth Century as Described by Scultetus

Johannes Scultetus (1595–1645) wrote his book *'Armamentarium Chirurgicum'* with an evident didactic objective, given the precision and accuracy of the illustrations of the instruments, of the surgical techniques and of the explanatory text [1]. Of the 43 plates (*'tabula'*) included in the book, 6 are dedicated to the instruments of cranial surgery and 4 contain figures related to cranial surgery, although the latter only has one figure on this subject. Scultetus and collaborators accurately state that 'the reader of the *'Armamentarium Chirurgicum'* received a state-of-the-art education in medicine and surgery of the seventeenth century' [2].

Scultetus describes the technique of cauterisation of the 'supra-coronal cranial commissure' *('supra suturam coronalem'*) in tabula XXX (*'De apparatu & modo fonticulum supra suturam coronalem inurendi & deligandi, vulnera capitis in crucem dilatandi, rimulas cranii dubias abradendi'*). Figures I–VII show the instruments and technique. It shows how to calculate the cauterisation point drawing a biauricular line that crosses with sagittal midline. The point, showed in a dried skull, is located just about one centimetre anterior to bregma. The surgical technique consists of a small scalp opening and introducing the cautery through a perforated cylinder. Finally, it details the placement of a Galen's bandage.

The surgical instruments and technique for management of linear fractures, with a gap in between, are showed in Figs. VIII–XII. The skin is opened in a cross-shaped incision. Then a scraper is used to remove the fracture borders.

The technique for making a right front trepan hole is described in tabula XXXI (*'De apparatu & modo vulnera capitis in triangulum secandi cranium modiolis peforandi, & caput fasciá cancro dicta deligandi'*). The instruments for the procedure are shown in Fig. I. The incision in the skin is V-shaped, raising a small triangular flap. The cranial perforation is done with a *'modiolus'* mounted on a T-handle (Fig. V). A complex

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bandage is showed and finally the application of this complex crab dressing is described with precision.

Scultetus describes a great number of instruments for the elevation of depressed skull fractures. The technique for the use of all of these surgical instruments is in tabula XXXII (‘*De ratione elevandi vectibus cranium depressum, abrumpendi forcipibus ossiculae membranas cerebri pungentia, excidendi serra versatili foraminum modiolis fractorum intersticia, & generali vulnerum capitis medela’*). The table shows the different ways of treating cranial fractures with subsidence, with probable damage to the dura, using the different instruments in a simple and direct way. Here it shows the use of *‘serratula versatilis’*, *‘tripolides’*, elevators and bone forceps (Figs. I–VIII). When necessary, Scultetus recommends the indirect elevation of the bone fragments by performing two perforations with the *'modiolus'* near the fracture, which are joined with a saw and, finally, the elevator is applied in this cutting line. All incisions on the skin are cross-shaped (Figs. IX and X).

Finally, Tabula XXXII shows only one figure about cranial surgery (Fig. I), showing how not to puncture the skull, after the cutting of the skin again with a cross-shaped incision. Scultetus uses as perforator a leg of a three-legged instrument he calls *‘terebellum’*.

20.2 Surgical Technique of Trepanation in the Eighteenth Century as Described in ‘L’Encyclopédie’

‘L’Encyclopédie’ describes the ‘state of the art’ of the trepanation in the eighteenth century, particularly the French style of trepanation. *‘L'Encyclopédie’* or the *‘Dictionnaire raisonné des sciences, des arts et des métiers’* was edited in France between years 1751 and 1772 under the direction of **Denis Diderot** and **Jean le Rond d’Alembert** [3]. It was aimed to gather and spread in a clear and simple way all the knowledge that had been acquired until then. It included 72,000 articles written by more than 140 collaborators. It contained many entries about the trepanning instruments, including the trepan, as well as crown, exfoliating and drilling trepans, lifters, lenticular knife and *‘tire-fond’* along with a long article that described the trepanation procedure. We must highlight how exhaustive, clear and accurate the definition and the description of the use of the instruments and the technique were. This entry was obviously written by **Louis de Jaucourt (1704–1779)**, a physician, philosopher and encyclopaedist who was an expert in this field. Among the prints in the collection, there were two about trepanation and its instruments.

According to *‘L’Encyclopédie’*, *‘Trépaner, terme de Chirurgie’* means carrying out a surgical intervention with a trepan. That is, making an opening on the skull to lift bone fragments that stick or press the dura mater or the brain or to evacuate the materials accumulated under the skull or to remove the bone fragment that are *‘cariés’*. This intervention was generally carried out as a consequence of wounds or blows on the head. He then described how to place the patient's head, which must be lifted, leaned on a support and placed so that the trephine crown could be used perpendicular to it. The bed should hang from a wall so that the assistants could be placed comfortably to hold the patient's head. The instruments were organised forming a line according to the order in which they would be used. Once everything was prepared, the surgeon took a crown trepan with a pyramid and placed it perpendicular to the skull. He checked if it was solid enough and spun it twice or thrice, making a mark on the skull. He then took the drilling trepan and carefully placed its tip on the mark that the pyramid had made on the bone (which serves as guide for the driller). He made a circle with the thumb and the index finger of the left hand, surrounding the *‘pomme’* of the trepan handle. He put the chin on the circle, making the handle spin from right to left with the three first fingers of the right hand until making a hole on the skull where the pyramid of the crown could fit *(‘Voyez cette attitude, fig. 1. Pl. XVII’*). Before removing the driller, it was necessary to spin half a turn from left to right without leaning the chin. This allowed removing the instrument from the hole where it was inserted in the bone.

The assistant in charge of the instruments disassembled the driller and placed a crown. Meanwhile the surgeon removed the bone sawdust that had been caused by the driller with the brush. The surgeon inserted then the pyramid in the hole made with the driller and spun the instrument from right to left, making a circular drill on the bone. If the crown was not applied perpendicular, the cut of the bone was not homogeneous around the whole circumference. The surgeon could notice it when more bone sawdust was produced in one side than in the other. He then had to push harder in one side than in the other to match the cutting depth.

When the crown went deep, it was rotated half a turn from left to right and removed. While the assistant disassembled and cleaned the crown with a small horsehair brush, the operating surgeon palpated with a stylet and removed the bone sawdust. An indicator of the cutting depth is that the bone sawdust from the diploe is blood stained and it can be easily cut, whereas the sawdust from the internal table is white and harder to cut. The surgeon had to be very careful in that moment not to dip inside the dura mater. Every time the crown teeth blocked they rotated the instrument in the opposite direction, removed the bone sawdust, palpated with the stylet and started cutting again. The cut was repeated until the surgeon perceived the bone was loose. Then it could be lifted with a dissector in *'feuille de myrte'*. When the piece of bone had been removed it was important to homogenise the unevennesses of the internal circumference of the hole that might injure the dura mater when it pulsed. A lenticular knife was used for this purpose.

If there was an effusion over the dura mater the patient was recommended to take a deep breath and then plug his or her nose to help him or her evacuate the effusion. This procedure was not always possible. A lethargic patient does not follow the instructions. Sometimes the openings were made in the declining areas. In these cases, it was occasionally needed to inject liquids through the counter-openings. As the trepanation was sometimes carried out due to bone fragments that compressed the dura mater or the injured membranes or penetrated in the brain, it was necessary to lift those fragments with a lifter.

20.3 How the Old Restrictions and Fears for Trepanation Are Slowly Overcoming

As we have already said, the most frequent indication for trepanation was open head traumas with skull fractures. The basic surgical procedure was as follows along decades. The hair was shaved with barber razors. The wounds were enlarged with additional incisions that frequently had a cross shape. When there was much attrition of the pericranial soft tissues surgeons carried out a circular resection of such soft tissues leaving a denuded bone (*'scalping'*). The concept of soft tissue flaps only appeared at the end of the nineteenth century when surgeons started carrying out trepanations in unbroken skulls to treat intracranial lesions. These incisions on the soft tissues were made with different types of knives. The bleeding of the scalp, which is pretty abundant, was initially controlled by compression or with poultices. The trepanation was carried out a few hours or days after, when a natural haemostasis was achieved. The cauterisation method was applied later and finally the catgut ligations or the haemostatic forceps were introduced, which allowed to carry out the cranial exposure and trepanation in the same surgical time.

The technique and the instruments used for trepanning have been well described, as well as their changes in the design throughout the centuries and their geographical peculiarities. For this reason, we are not going to repeat it. Once physician decided to carry out a trepanation, the next stage was to select by the surgeon the point where the trepanation was allowed. The guidelines of the Hippocratic texts imposed a series of restrictions that were considered valid during the Middle Ages and throughout many centuries. These restrictions were the following: it was not allowed to trepan on cranial sutures, it was not allowed to trepan in areas of the skull that were covered by muscles and it was not allowed to trepan on the middle line of the frontal bone. All these restrictions were criticised and abandoned as time went by.

The fear of trepanning on cranial sutures persisted over centuries since the Hippocratic texts, which expressly prohibited it with no additional explanations [4]. Some authors described later the clinical symptoms derived from it, which could even lead to death. The sutures were considered over centuries on areas of the skull where the dura mater was fixed to the cranial bone. For this reason, they should be avoided so that the dura mater did not detach. This is not a relevant observation in the practice of modern neurosurgery and seems not to involve any additional difficulty in any case. The dura mater adheres to the deep side of the cranial vault, particularly in aged patients with hyperostosis frontalis interna. This is not particularly significant in sutures.

The problem is the existing anatomical relationship between the cranial sutures and the dural venous sinuses. It was not until the sixteenth century when the anatomical observations proved undoubtedly the relationship between part of the path of some sutures and the dural venous sinuses. The sagittal suture is a dangerous area to be trepanned as the superior sagittal sinus runs under it and has multiple venous lakes and Pacchionian granulations irregularly spread beside it. They make the bone thinner in some focal areas, where the dura mater is also thinner. The sinus, the venous lakes or the granulations can be easily pierced during the trepanation, causing a massive haemorrhage. They also avoided the bregmatic area, particularly in children, as the fontanelle of this area is open in infants and it is considered a delicate region. There is no sagittal suture in the frontal bone as this is a single bone and the sagittal sinus runs along the middle line, without involving any suture except in those cases with a persistent metopic suture. However, the coronal and lambdoid sutures have no relationship with the dural sinuses along most part of their paths. The craniometric point asterion, which is the confluence of several sutures, has a close relationship with the angle where the transverse sinus turns and becomes the sigmoid sinus, which is again a dangerous area. These sinuses usually have no adherences but they run embedded in the internal side of the skull along a bone groove. This also makes them vulnerable. In addition to this, large cortical draining veins reach the dural venous sinuses, such as the veins of Rolando, Trolard or Labbé.

It is evident that trepanning on these particular areas of the sutures was (and still is) potentially dangerous. The trepanation restriction of the middle line along the sagittal sinus seems logic. It is still avoided when drilling the skull. It was a feared area until modern high-speed motors were incorporated to neurosurgery. Anyway, many neurosurgeons still make paramedian holes to lift the bone and cut the bone over the sinus with a vertical cutting saw. This manoeuvre still involves many risks.

However, the trepanations in primitive cultures, particularly in those from South America, include examples of very large openings that involved long segments of the dural venous sinuses and that showed clear signs of survival. This has been explained by the fact that these trepanations were carried out with abrasive methods. This way the probability of injuring the dura mater or the venous sinuses was lower than when drilling the skull with metal instruments with saw cutting teeth.

Surgeons overcame the fear of trepanning on sutures thanks to particular observations that the different authors cautiously started including in their works. Thus, **Jacopo Berengario (1457–1530)** pointed out that he had already trepanned on sutures with no consequences in the sixteenth century. However, the general recommendation that persisted over centuries still suggested trepanning on either side of the suture if it was necessary. **Girolamo Fabricius d'Acquapendente (1537–1619)** expressly mentioned the dramatic haemorrhage that could happen when trepanning on a suture, probably because he did it on one of them that was closely related with a dural venous sinus. This marked the difference between trepanning on a suture and breaking a venous sinus. The point of view started changing from the seventeenth century. Surgeons warned about the importance of trepanning carefully near the sagittal suture. They later admitted that it could be done without any large risk. They finally started describing cases of how to control the haemorrhage of the sagittal or transverse sinuses by plugging them. Nowadays the dural venous sinuses still are a dangerous area for trepanations and craniotomies. Although their anatomy is well known, they can be identified during the surgery by neuronavigation and we have suitable instruments, it is possible to find intraosseous extensions, anatomical variants or accidental injuries of their walls with severe intraoperative bleedings.

Another area that has been feared since ancient times was the base of the middle line of the frontal bone, as well as the whole supraciliary region, as it includes the frontal paranasal sinuses. The frontal sinuses were avoided until surgeons had an adequate anatomical knowledge thereof due to their different development depending on the age, anatomical variations, existence of walls and a double wall that could be mistaken and was always a clearly septic cavity. Moreover, it involved problems related to trepanation due to the weakness of its superficial wall in traumas and the tendency to suffer from infectious complications and primary or post-traumatic fistulas.

The most posterior area of the middle line was also avoided with a good reason as the external occipital protuberance can be found here. The thickness of the bone is significant here and below it there is a great confluence of dural venous sinuses forming the torcular Herophili or torcula.

Avoiding the areas of the skull covered by muscles was a restriction that mainly had to do with the haemorrhage that is produced when cutting and detaching them to denude the bone and due to the larger diameter of the pericranial arteries in the basal areas of the head, as they have not branched yet. This problem is magnified in the nuchal muscles, where the skull is very deep and its direction is not optimal to apply a trepan. It is curious that the temporal fossa covered by the temporal muscle was avoided, even though the bone of this area is very thin and has a great incidence of traumas that involve serious consequences for the patient. When the author was a child, people were afraid of being hit or suffering from a wound on the temple as it was considered serious and potentially fatal in popular culture. All these restrictions were abandoned thanks to the empirical evidence that proved that they could be omitted or solved.

Once the cranial opening was completed by extracting the fragments, making a single or a multiple trepanation or by enlarging the trepanation with a saw or a chisel, the blood, pus, bone fragments or foreign bodies were removed from the epidural space. The depth limit for the surgeon has been the dura mater over centuries [5]. Ancient surgeons did not open the dura mater under any circumstances. However, open traumas with bone fragments or projectiles that pierced the dura mater forced them sometimes to explore the intradural space. Brain wounds were considered fatal over centuries. When a bone fragment or foreign body was suspected or evidenced to be lodged in the brain surgeons recommended not trying to remove it. Once again, some particular observations proved that this was feasible and that it could save lives. For this reason, surgeons started recommending to open the intact dura mater if an underlying lesion was suspected as the dura mater looked taut or bluish. The opening of the dura mater became necessary when non-traumatic brain lesions were clinically diagnosed. The exploration of the subdural space was then incorporated as a routine manoeuvre in the surgical technique of trepanation. The different brain examination techniques that searched for subcortical lesions were also introduced in this moment. They included palpation, punctures, corticectomy, cortical electric stimulation, examination with the surgeon's fingers and brain resection.

However, surgeons came across with a new depth limit when they surgically explored the brain at the end of the nineteenth century. It was the lateral ventricle. **Antoine Chipault (1866–1920)** briefly and openly described what he observed in his patients: *'Les larges interventions intra-cérébrales que nous venons de décrire se heurtent du reste à un écueil qui paraît insurmontable: l'ouverture large des ventricules. Cette ouverture entraîne, en effet, constamment, dans un délai rapide, ne dépassant pas parfois quelques heures, la mort de l'opéré, avec des phénomènes hyperthermiques et convulsifs qui ne sont point d'origine infectieuse et semblent simplement dus à la déperdition du liquide céphalo-rachidien'* (The large intra-cerebral interventions which we have just described face, moreover, an obstacle which seems insurmountable: the wide opening of the ventricles. This opening causes, in fact, constantly, in a rapid delay, not exceeding sometimes a few hours, the death of the operated, with hyperthermal and convulsive phenomena which are not of infectious origin and seem simply due to the loss of the cerebrospinal fluid) [6].

This progressive invasion of the intracranial space searching for the pathology only took place when the surgeons were confident enough of his command on the skull-opening technique and the complications were under control. Consequently, the cranial opening became as the first surgical time to solve the intracranial pathology that justified the intervention as it required a trepanation. As we have already mentioned, all this was the result of gaining medical, neurological and surgical knowledge. These different areas of knowledge fostered each other and led to the creation of the neurosurgery linked to modern craniotomy at the beginning of the twentieth century.

There have been other problems that have concerned surgeons who carried out trepanations time and again throughout centuries. There has always been a constant concern about the possibility that the drilling instrument, either the trepan or the trephine, might accidentally dip in the skull. Another issue that was discussed were the clinical consequences of keeping the cranial hole that resulted from the open trepanation.

Authors from different times since the Hippocratic texts have been concerned about warning surgeons about dipping the drillers in the skull once the trepanation was over or through cranial fractures. This involved a high risk of injuring the dura mater and the brain. As a consequence, braking systems with all kinds of stopping mechanisms have been designed from the beginning so that the cranial drilling instrument was unsinkable (*'abaptista'*). Modern drillers coupled to electric or pneumatic motors also have spin clutch systems as well as braking and mechanical locking systems to avoid dipping them. These modern instruments can also fail [7]. However, the plunging (*'baptista'*) was more frequent in mechanical instruments than in motor-driven instruments. The problem was pretty frequent and could be indeed very serious for the patient. The frequency of these events in real surgery was (and is) high. A survey that was recently carried out in Great Britain and in Ireland showed that two-thirds of the neurosurgeons had experienced a plunging event. One-fifth of the surgeons had experienced more than one. The severity of the event was even truly relevant for the patient. A quarter of the cases showed an intracerebral haemorrhage and their risk of death and severe neurological deficit significantly increased. To avoid these accidents, it was recommended not to trepan near the fracture lines and brush the bone sawdust from the drillers as it blocked the braking systems.

Patients with cranial openings carried out in the trepanation or craniotomy might develop symptoms derived just to keep the skull cavity open [8]. This was repeatedly described in medical texts throughout history. The so-called syndrome of the trephined involves motor, cognitive and speech symptoms, headaches, dizziness, pain or discomfort in the place of the decompression, fear and depression. These complains can appear weeks or months after making the cranial opening and improve after a cranioplasty. They affect patients of all ages and of both sexes with openings in different locations. They are more frequent in traumas, large craniotomies and over time. Surgeons of all times recommended applying metal or leather discs onto the defect that were fixed with strings when the patient showed these symptoms. The physiopathological mechanism of this syndrome is not clear. It always involved weather factors in ancient texts, such as temperature and atmospheric pressure shifts. Nowadays the role of the atmospheric pressure shifts is accepted along with changes in the blood supply of the brain or in the cerebrospinal fluid flow or changes in the brain metabolism that are related to the skin depression and the compression of the underlying brain. A more severe problem for the trephined was brain herniations. Luckily, they have been forgotten as osseous decompressions in tumours were forbidden and an early repair of the cranial defect is carried out nowadays. Infection was an additional problem for brain herniation because the approaches were often carried out with a circular skin resection and the evolution of the wound involved the supposed benefit of the 'laudable pus' and a later cicatrisation and healing by second intention.

20.4 Where the Trepanations Were Carried Out

Last, we must comment the hygienic environment in which the trepanations were carried out. The place where the trepanations were carried out has changed throughout these centuries, in the same way that the surgical scenarios changed. Most part of the interventions recommended by physicians were carried out by surgeons at the patient's homes until the eighteenth century. Many texts vividly illustrate scenes of trepanations, where the place, patient, surgeons, assistants and witnesses of the surgical intervention are appreciated. It is also possible to appreciate, in some cases, the surgical instruments and the way to handle them by the surgeon. These are scenes of great historiographic value, since they present us in the social and cultural context of trepanation, and allow us to be witnesses at the time of this surgery.

The illustrations from the sixteenth century that were included in the book *'Chirugiae Universalis Opus* Absolutum' published by **Giovanni Andrea della Croce (c1515–1575)** in 1573 and in the cover of the book *'La chirurgie françoise, recueillie des anciens Medecins et Chirurgiens avec plusieurs figures des Instrumens necesseres pour l'operation Manuelle'*, which was published by **Jacques Guillemeau (1550–1584)** in 1594 give us a good idea about the trepanation environment.

The edition of the book of della Croce of the year 1596 includes illustrations with scenes of the environment where the trepanation takes place [9]. The book includes the repot of six cases of head trauma to complete the chapters dedicated to the subject. Here three of the interventions carried out are illustrated (Fig. 20.1). The scenes have common characteristics. della Croce's illustrations show that the intervention was carried out in the patient's bedroom. The surgery is done in the patient's bed, lying face down and with the head resting on a pillow. The surgeon seems to be applying a *'rugine'* in the first case, performing a trepanation with a trepan with straight handle (*'canulus'*), rubbing it between both hands in the second and, finally, doing a trepanation with a brace-handle trepan in the third case. The surgeon works alone, without

Fig. 20.1 Three illustrations taken from the book by Giovanni Andrea della Croce (della Croce, GA. Chirurgiae universalis opus absolutum. Venetiis: Iordanus Zilettum, 1596)

Fig. 20.1 (continued)

the collaboration of any assistant. Nevertheless, there are always people helping the surgeon by offering instruments or dressings. In the first two scenes there is a person dressed elegantly, looking the procedure, probably the physician.

The patient's ears are plugged with cotton. This recommendation had also been followed since ancient times, but not all surgeons were so dogmatic about this issue. They also tried to hide the trepanation instruments so that the patient could not see them. The room is always full of families, relatives and servants, some distressed or prying and others helping. The room is locked in the first and third scenes, and the window is covered with curtains. Always they use braziers to warm up the room, as it has always been considered that there was no greater danger for the brain than cold. Different animals run or rest on the floor of the room, a dog in the first scene, a cat and a rat in the second and a dog and a rat in the third.

The illustration of the cover of Guillemeau's book shows a similar scene [10] (Fig. 20.2). On the opening page of the book several surgical scenes are represented, the upper right representing a trepanation, where the patient is lying face down and an assistant holds his head, which is supported by a pillow. The surgeon uses an instrument with a brace handle and a crown. Behind, on the wall, there are different trepanning instruments hanging. The other two persons are a surgeon doing a wound dressing on a patient's head, who is sitting on the bed.

The scene is almost identical to the image that showed a trepanation in London almost a century later. It was included in the book *'A Compleat Discourse of Wounds'* by **John Browne (1642–¿1700)**, which was published in 1678 [11]. On a plate of the book there is a scene of a trepanation that takes place in the patient's room (Fig. 20.3). An assistant holds the head of the patient, placed in lateral decubitus, and another holds the body. The surgeon uses a conical crown trephine mounted on a T-handle on 'crane wings', following the British style of trepanation. The surgeons' clothes were characteristic of that time. The case attended and precisely portrayed by **Lorenz Heister (1683–1758)** in 1753 also showed the same scene. In this case, Heister went to the patient's house and visited

Fig. 20.2 Segment of the title page of the book by Jacques Guillemeau showing a trepanation (Guillemeau J. La chirurgie françoise, recueillie des anciens medecins et chirurgiens avec plusieurs figures des instrumens neceseres pour l'operation manuelle. Paris: Nicolas Gilles; 1594)

Fig. 20.3 Figure showing the British style of trepanation done with a crane-wing T-handle trephine in the bedroom of the patients, by John Browne (Browne J. A compleat discourse of wounds. London: E. Flesher; 1678)

him several times. He stated that the trepanation was carried out by surgeons without his direct supervision [12]. René-Croissant Garengeot (1688–1759) in the *'Nouveau Traité des instruments de chirurgie les plus utiles, et de plusieurs nouvelles machines propres pour les maladies des os'*, describes the so-called chin support'. An illustration shows the operation, performed on the patient's bed, with the assistant holding his head. The surgeon applies the trepan with the chin support technique. This is an example of the French style of trepanation [13]. One illustration in 'L'Encyclopedie' [3] shows a scene where the cranial trepanation is represented, with the chin support being used (Fig. 20.4). The assistant holds the head of the patient, which seems supported on a hard plane, which suggests that may be the head of a corpse. The position of the hands and fingers of the surgeon, somewhat artificial, are accurately described in the text and correspond exactly to those in the figure. This is again an example of the French style of trepanation.

Fig. 20.4 Trim of a page of '*L'Encyclopédie'* showing the French style of trepanation with chin support (Diderot D, D'Alambert R. L'Encyclopédie. Paris; Chez Briasson, David, le Beton, Durand: 1751–1772)

Apart from these occasional scenarios for trepanations, other places in which trepanations were more often carried out were field hospitals on the battlefields as well as sanitary establishments and dispensaries in mining regions where cranial traumas were very frequent. We have already described the healthcare conditions in the American Civil War and in the copper mining region in the South of England. They both had clearly better clinical outcomes than large hospitals in big towns in that time. The trepanation at hospitals only became popular when the general and local anaesthesia was widespread and the aseptic and antiseptic techniques were introduced in the last third of the nineteenth century. As a consequence, trepanations were carried out in a pretty safe way in operating rooms.

In the book by Alexis Clerc *'Hygiène et médecine des deux sexes. Sciences mises à la portée de tous'* published in 1885, a scene of a trepanation, probably carried out in a hospital bed, is shown [14] (Fig. 20.5). The patient is face up and dressed in street clothes, although bedridden and covered and immobilised. The surgeon


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matique; la *portion mastoïdienne*, qui correspond à l'apophyse mastoïdienne; la *portion pierreuse* nait de la face interne de l'os, est appelée aussi le *rocher* ou l'*apophyse pétrée*, renferme dans son intérieur tous les organes immédiats de l'audition. Il s'articule avec le sphéroïde, l'occipital, le pariétal, l'os de la pommette et le maxillaire inférieur.

TRÉPAN. — TRÉPANATION.

TEMPORO - AURICULAIRE ou **TEMPORO - CONCHINIEN** adj. et n. m. Le muscle supérieur de l'oreille.

TEMPORO - MAXILLAIRE adj. Qui appartient à la tempe et à la mâchoire. — *Articulation temporo-maxillaire*, entre le condyle de la mâchoire, la portion antérieure de la cavité glénoïde, et l'apophyse transverse du temporal. — *Nerf temporo-maxillaire*, la supérieure des trois branches de division du nerf facial.

TEMPORO - SUPERFICIEL adj. et n. m. Branche collatérale du nerf maxillaire inférieur.

LIV. 262. A. CLERC. — HYG. ET MÉD. — ÉD. J. ROUFF ET C^{ie}. LIV. 262.

Fig. 20.5 Scene of trepanation by Alexis Clerc (Clerc A. Hygiène et médecine des deux sexes. Sciences mises à la portée de tous. Paris: Jules Rouff; 1885) and the assistants are dressed in street clothes and wear aprons. Curiously, the trepan is applied transversely, without the head being supported on a safe plane, only held by an assistant. In the same year Terrier and Péraire include a figure in '*L'opération du trépan*' where a cranial trepanation is represented [15]. As we are in the end of the nineteenth century, it is indicated in the text that the support is no longer made in the chin, neither in the forehead nor in the chest because it goes against the most elementary antisepsis norms. At the foot of the figure the author claims that the sleeves of the surgeon's dress should not reach the wrist but should be gathered at the height of the elbow. The patient is lying on his back and resting on a pillow. A remarkable wax model work of an early-twentieth-century trepanation by an unknown author entitled *'Using the trepanning method (with drill) to penetrate the skull'* can be found in The William Bonardo Collection of Wax Anatomical Models, founded by a Swiss painter in the early twentieth century and auctioned by Christies in 2001. The author of these models is unknown, but it is well known that it was later inherited by owners of a 'carnival freak show', William Bonard and Lily Binda. They made their funds by exhibiting these figures in settlements [16].

20.5 Conclusions

In conclusion, if we analyse the situation of cranial trepanation at the end of the nineteenth century from a current perspective we must admit that there were many lights and shadows. On the one side, all barriers that had been imposed since the Hippocratic times had been overcome. The design of drilling systems had been settled down with the trephine crown on a T-handle in English-speaking countries and a brace handle in mainland Europe. The treatment of intracranial pathology beyond traumas and their complications had already started. Mortality rates had been significantly reduced, even though they still were concerning. However, the cranial opening achieved by trepanation and the alternative options to enlarge it seemed to be ineffective to solve the challenges of the new intracranial and intracerebral lesions diagnosed by neurologists that required a surgical treatment. Luckily, there were no more collapses of this type of surgery as craniotomy was invented. It soon substituted trepanation, as we will later discuss.

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21 Evolution of the Surgical Instruments for Trepanation and Trephine in Modern Age

21.1 Evolution of the Trepanation Instruments

As we have observed, it is possible to accurately track the evolution of the surgical instruments used for trepanation in the historical period from the end of the Middle Ages until the end of the nineteenth century thanks to a great number of documents and original sources. The first medical texts written in Latin or vernacular languages included descriptions and drawings that probably had nothing to do with reality at first. However, the descriptions and illustrations soon showed the original instruments and finally there are original instruments from the eighteenth century available in museums and collections. This great amount of information allows us to come to the discouraging conclusion that technical and technological innovations were scarce over centuries, with frequent reinventions. The improvements accumulated in the end of the period that is the subject matter of the study in this chapter. This revealed the revolution that took place at the end of the nineteenth century with modern craniotomy.

As for drilling instruments, the basic models described in the Hippocratic texts (which were probably used in ancient times) persisted with just a few variations. The punch-like driller or borehole driller, which was a natural evolution from the *'terebra'*, was not significantly modified as its design did not admit many variations. Its use probably became more limited over time. They were used in Hippocratic and medieval texts to make small holes with the aim of draining cranial infections. Several grouped or consecutive drills were made to resect large portions of bone. They made up a circle or a polygon that enclosed the lesion to be resected. As cranial trepanations were mainly focused on head wounds and traumas since ancient times, small drills like those achieved with the borehole drill were not useful to remove fractures. This was the reason why this type of drillers became obsolete and only the pyramid-shaped tip design persisted to start the perforation. The tip of the central pin or the pyramid of the crown driller or trephine was then coupled to that first hole in order to carry out the definitive drill.

Crown drillers or trephines, which were a natural evolution of the *'modiolus'*, only introduced a few innovations concerning the design. The basic elements of ancient *'modiolus'* can be found in the trephines from the end of the nineteenth century. The hollow cylindrical crown with serrated edge and the hollow truncated cone-shaped crown with striated or grooved side walls were the two basic models that were repeatedly manufactured without significant variations over centuries. The braking system of the cylindrical crowns with an external stop or a height-adjustable cap started disappearing whereas truncated cone-shaped crowns, which did not require any coaxial element as the braking system consisted of the shape of the crown itself, became more popular.

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The old central pin allowed to classify the Medieval and Renaissance crowns in males and females depending on whether they had or not such element. This pin persisted and became an essential element of the trephine, the pyramid. This pyramid could protrude more or less from the cutting level in a variable way according with the requirements of the surgeon. The function of the pin was to become a stabilising element of the crown when the instrument spun in ancient times. This function persisted later. However, it became easier as they made a first hole on the outer table with a punch. The tip of the pin was then coupled to this hole. The possibility of changing the length of the central pin allowed to use it as an exploration element for the drilling depth. As the tip of the pin was ahead the cutting crown, the pin got to pierce first the internal table and thus the intracranial space. By checking how far is the tip of the pin when compared to the cutting edge after removing the cutting crown, the surgeon knew how much bone he still had to cut. He could then adjust the manoeuvre with new corrections of the progress of pin and by palpating with a probe the cutting edge of the crown. When there were already several points on the margins where the internal table has been broken the trephine was removed and the *'tirefond'* is inserted in the same central hole made with the trephine pin to break the rest of the bone and remove a disc of skull. As an alternative option, a light lifter can be used. Finally, the lenticular knife was used to regularise the borders of the bone removing all small irregularities and splinters.

The largest diameter of the trepanations made with trephines did not exceed 4–5 cm because drilling with large crowns was very inefficient in mechanical terms. We have previously described the different options that surgeons had to enlarge cranial openings. However, this manoeuvre was not very frequent. Hence, many linear fractures were treated by scrapping with *'rugines'*. However, as the indications for trepanations were fractures and as the treatment of a fracture consisted of removing, surgeons endeavoured to include the whole fracture within the trepanation. This forced surgeons to make several trepanations, one after another. However, physicians already affirmed in the Middle Ages that it was not necessary to trepan along the whole path of the fracture. It was admitted that fractures themselves did not require either active or preventive treatment in the eighteenth century. It was also accepted that the application of the treatment of fractures was the decompression of the depressed fragments, drain of blood or purulent accumulations and removal of foreign bodies. All this was the reason why the design of the cranial opening was modified. Other types of cranial surgery were carried out to remove depressed bone fragments. In these cases, trepanation was not always required and it was generally avoided if it could be solved by other means.

The contributions and modifications of the handle that supported the drilling instrument were more interesting. In this regard, there are not many references about it in the old texts. Hippocratic texts and later Medieval texts related that the *'terebra'* was warmed and had to be repeatedly removed and cooled with water to avoid burning the bone. This suggested that the manual movement of the instrument was not enough for so much friction and thus acceleration systems had to be used. The acceleration systems with strings were applied to longitudinal handles. They were only shown and illustrated in some medical texts from the end of the fifteenth century and the early sixteenth century. They soon disappeared and were substituted by borehole and brace handles. These handles were used without significant changes of their design until the end of the nineteenth century. However, in the real neurosurgical practice they were used until the second half of the twentieth century. Borehole or brace handles are more efficient than the straight ones and did not require acceleration systems or cooling. Drillers were interchangeable since their beginnings in order to make the most of the same handle. As we have already mentioned, the final successful model was the trephine-like driller, which followed the *'modiolus'* design. It was mounted on a T-handle in English-speaking countries and on a brace-like handle in mainland Europe.

21.2 An Instrument Called *'Tirefond'*

We are now going to describe, as an illustrative case, the modifications concerning the design and the use of a particular instrument called *'tirefond'*. As we have already explained, the core element of the instrument was a spiral threaded tip or screw tip. The changes of the design and use can only be understood when tracking the historical evolution of this instrument. The design of the tip has probably led to mistaken interpretations about its real application. Some authors have argued that the *'tirefond'* was a cranial driller. However, it seems evident that the hole created would be tiny and that, in any case, the instrument would be firmly anchored to the bone. Other authors suggest that it was aimed at being screwed to bone fragments of fractures, allowing thus to remove such fragments safely. The instrument is clearly inefficient and dangerous for this purpose as it requires the fragment of bone to be attached and fixed to the rest of the skull so that the *'tirefond'* can be screwed without dipping inside the skull. For this reason, its use in depressed ping-pong fractures of infants seems more logic, and actually it was recommended for this purpose. Everything seems to suggest that its real application was finally to catch the bone discs produced after sawing with the trephine crown. They were captured by screwing the *'tirefond'* to the same central hole made with the trephine pin before cutting completely the internal table. For this reason, the handle was normally light and, usually, it had three legs. The two other legs had light (not massive) lifters such as those used to lift fracture fragments.

The mistakes about the use of the *'tirefond'* were probably due to the first illustration of von Gersdorff's torcula from the sixteenth century. As we have already mentioned, the first instrument with a spiral threaded tip was shown on the torcula invented by Von Gersdorff (1455–1529). It was described in the book *'Feldtbuch der Wundartney',* which was written in 1517 [1]. In the book it is used on an area of skull with uneven margins that suggests a depressed fracture, which would be lifted with the aforesaid instrument. The design of the torcula with its threaded tip instrument appeared repeatedly throughout history. It was shown, for example, in the books written by Ryff, Paré, Dionis or Heister. It disappeared later, along with the torcula itself.

The spiral threaded tip has also been mounted on other handles. It was in the works of Walther Hermann Ryff (c1500–1548) where we first found a borehole with a threaded tip [2]. It was drawn beside another borehole with sharp tip, which he called *'trepana'*. The instrument with a threaded tip was also included in the later edition of '*De fractura cranii'* published in 1651 and written by Jacopo Berengario (1457–1530), who called it *'trepanum'* [3]. It also appeared in the book *'Opera observationum et curationum medico-chirurgicarum, quae exstant omnia'*, written in 1682 by Wilhelm Fabry von Hilden (1560–1634), who called it *'terebellum'* and in many other authors' books. This spiral threaded tip borehole design (not useful as perforator) was abandoned later.

The French author Laurent Joubert (1529–1582) was the first one who used the name *'tirefons'* to refer to the instrument with threaded tip. This surgeon wrote the book *'Annotations de M. Laurens Joubert, sur toute la chirurgie de M. Guy de Chaulliac'* in 1559 [4]. In his book he commented the works written by Guy de Chauliac (c1300–1368), a French surgeon who published *'Chirurgia Magna'* in 1363, that is, more than 200 years earlier. In this book, Joubert drew the instruments attributed and had already been used and named by Guy de Chauliac, regardless of their authenticity. Joubert included illustrations of a three-legged or Y-shaped instrument, which he called *'tirefons à relever les os'*. One of its legs has a threaded tip and the two others served as lifters.

Ambroise Paré (1510–1590) described and showed a similar instrument in his work *'Methode curative des playes et fractures de la teste humaine'*, which was published in 1561 and where he explained the instruments required for a trepanation. However, there was a difference as the lifting legs had different lengths. He called this instrument *'tirefons à trois branches'* [5]. There was another variation of this instrument soon, the *'tirefonds à trois pieds'* which was described by Jacques Guillemeau (1550–1584) in his work *'La chirurgie françoise, recueillie des Anciens Medecins et Chirurgiens avec plusieurs figures des Instruments necesseres pour l'operation manuelle'*, published in 1594 [6]. It was a star-shaped instrument with three legs, each of them having a threaded tip of a different diameter. He also included another *'tirefond'* with three different legs: one with a threaded tip, another with a lifting tip and the third one with a punch tip. Many other French, British and German authors described the same instrument with the same name and different combinations concerning the use of the three legs (thread, lifter, punch) until the beginning of the eighteenth century.

This Y-shaped design and the multiple uses of the instrument depending on the different end and function of the three tips abruptly disappeared later. This way, a *'tirefond'* that was only a handle with an extension that ended in a spiral threaded tip appeared in the first decades of the eighteenth century. It was exclusively used for being screwed to the hole made by the pyramid on the bone. This instrument was described by René-Croissant Garengeot (1688–1759) in his book *'Traité des opérations de chirurgie... avec les bandages qui conviennent à chaque appareil'*, which was published in 1720 [7]. The *'tirefond'* was only used from then on to break and remove the disc of bone obtained after sawing with the crown. The rapid evolution of this new design can be tracked in the French school designs made by Garengot, Dionis or Lesne in the eighteenth century and later by Bourgerie.

The functioning of this model of *'tirefond'* is accurately explained in *'L'Encyclopédie'* or in the *'Dictionnaire raisonné des sciences, des arts et des métiers'* which was edited in France between years 1751 and 1772 under the guidance of Denis Diderot and Jean le Rond d'Alembert [8]. However, this book states that it was an unnecessary and even completely useless instrument because if the disc of bone is firmly adhered it won't be lifted and will break in the area of insertion of the instrument. On the contrary, if it has been properly sawed, any type of lifter with the suitable size or shape will be enough to easily lift the bone. This last design of *'tirefond'* was never implemented in English-speaking countries. Finally, it was completely abandoned throughout the nineteenth century.

The design or use of other instruments was also modified. An example of this was the *'meningophylax'*, which turned into a lenticular and then into a lenticular knife and finally disappeared. There are neither archaeological remains nor representations of the *'meningophylax'*. However, the first drawings by della Croce and Alcázar illustrated it as a mere sheet coupled to a handle similar to a bayonet. The supposed application was to separate the dura mater from the bone. The sheet turned later into a lenticular enlargement placed on the end of light straight handle. The application was the same but it would be handled perpendicular to the bone, which would allow to explore the epidural space through a smaller hole, just depressing the dura mater. A later modification involved a bigger handle and a cutting edge, keeping the lenticular enlargement on the end. The instrument was called *'lenticular'*. The instrument was no longer used for separating the dura mater and exploring the epidural space and turned into a cutting instrument for the bone spicules and rims on the edges of the trepanation. It could be used on large spicules by tapping on the handle with a hammer or on small ones by manually peeling them. For this reason, the instrument is now called 'lenticular knife'. Finally, the instrument was no longer shown in instrument descriptions or prints of the nineteenth century.

Contrary to those instruments that have been modified, many others persisted over centuries without changing its design or use. Some examples of this were the mallets and chisels, the lifters and the bone forceps. Something similar happened with the scrappers, *'rugines'* and other instruments aimed at removing the periosteum from the bone.

At the end of the period of time of the Modern Age, the *'state of the art'* of the instruments that were actually useful for trepanning could be summed up in a very short list: a set of trephine-like drillers with a truncated cone shape mounted on a T- or brace handle (depending on the

Anglo-American or mainland influence), a set of punch-like drillers to serve as starters, a set of useful instruments such as bone scrappers of fragment lifters and finally a set of strong bone cutting and grabbing forceps. The saw was the tool of choice to enlarge the trepanation, along with the chisel and its compulsory companion, the mallet.

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22 Evolution of the Indications for Trepanation and Trephine in Modern Age

22.1 Indications for Trepanation and Trephine

We have already described the instruments used for trepanning as well as their evolution concerning the design and use along the Modern Age. We are now going to describe the changes in the indications and the surgical technique. It is a bit worrying that the surgical technique of trepanation barely evolved during the more than 400-year span that covers the period of time of the Modern Age. The indications did not change a lot either. The Hippocratic proposals were accepted at first. They were slightly criticised and modified at the beginning and then they were strongly disapproved. The actual modifications rapidly took place during the last decades of the nineteenth century. This moment was particularly intense and radical in terms of suggesting and adopting new scientific points of view and in terms of technological renovation. We are going to describe now the changes related to the indications of trepanation and the surgical technique from this perspective.

The indications of trepanation during the Middle Ages were the same ones that were included in the Hippocratic texts, i.e. only certain types of cranial traumas. The medical texts of that time studied and described the head wounds and those fractures that were eventually associated thereto. Cranial trauma continued to be the main indication of trepanation until the mid-nineteenth century.

Closed head injuries by direct impact due to blunt force trauma can be often associated to fractures. In these cases, if there is a pericranial contusion or wound, the fracture, regardless of its type, is normally located under. These fractures were diagnosed by surgical exploration of the cranial wound and surgeons recommended trepanning some of them. Some underlying fractures were not evident as they were linear, affected only the internal table or could be mistaken with cranial sutures. Some diagnostic methods were used to confirm the existence of these fractures, such as the examination with a scrapper to find steps or fissures, the tar or ink test where these substances were applied onto the denuded skull and marked the fracture line several hours after without staining the suture line, and other more sophisticated methods, such as the Valsalva manoeuvre, tapping the skull, string vibration or breaking seeds with the teeth. Finally, it was already known since the Hippocratic texts that there could be fractures away from the point of impact and the wound or soft-tissue contusion. They could only be suspected by the pain the patient suffered when directly pressing the fracture. The same difficulties in diagnosis and the same confusing situation in indications for surgery were present until the end of the eighteenth century when regarding trepanation for skull fractures.

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Authors from the Middle Ages recommended trepanning in certain open fractures, i.e. which were identified by examining the head wound. The trepanation of linear fractures had been promoted in ancient times. Surgeons recommended scrapping or carrying out a prophylactic trepanation in these fractures to avoid later complications during the eighteenth century. On the contrary, ancient surgeons were reluctant to treat and trepan depressed fractures as the instruments could dip in the brain, but this approach changed in the eighteenth century as surgeons were more prone to operate on.

At the end, some surgeons recommended trepanning in different places to those that had been subjected to the direct impact where the wound and the fracture seemed to indicate the area to be trepanned. This was due to the evidence that there were cranial and intracranial lesions away from the point of impact.

Nowadays, it is difficult to understand the criteria that surgeons followed to trepan their patients. At that time, different authors did different classifications of the skull fractures, some of them very complex. The lack of accurate diagnostic techniques and even reliable data from the surgical examinations or necropsies makes it difficult to identify and track unequivocally the classification of fractures and for which types of fractures the trepanation was indicated and applied by each surgeon.

Along centuries, also the description of the clinical symptoms was vague and confusing and does not help us either to answer the question of which patients should be trepanned. Strong clinical criteria were introduced only at the end of eighteenth century after identifying the concussion or initial alteration of the level of consciousness as an unspecific result of the cranial trauma and recognising the focal neurological symptoms of brain compression that usually appears later. These clinical data started being taken into consideration to recommend trepanning along with the structural injury of the skull itself by way of fractures. Although brain compression became a strong indication for trepanation, the symptoms of brain compression and brain inflammation due to congestion or swelling are similar and lead to disappointing results after trepanation. The cranial surgery that was carried out by army surgeons at war changed the indications and they started trepanning earlier. The higher casuistry allowed to clearly identify the signs and symptoms of brain compression. This also allowed to select more accurately those patients requiring a trepanation regardless of their type of fracture.

We have previously described the discussions between the different schools about the benefits of trepanation in trauma, particularly throughout the eighteenth century and at the beginning of the nineteenth century. A radical point of view supporting trepanation was represented by the English school, which was led by Percivall Pott. This caused that any cranial trauma was immediately subjected to trepanation in some mining areas of the South of England. The French and the German schools had passionate supporters and detractors concerning trepanation and some surgeons advocated the 'preventive trepanation'. The core concern of this vehement discussion was the high mortality of the intervention. This was the reason why trepanation was almost universally despised and abandoned. The trepanation went back only when the aseptic and antiseptic methods were applied. Mortality decreased significantly and surgeons started showing interest in trepanation again.

As the result, the indications of the intervention were broadened beyond traumatic pathology in the second half of the nineteenth century and the *'state of the art'* of the trepanation reached its greatest splendour at that time. However, most interventions were still carried out for traumatic pathology. We must point out that there was no new diagnostic method to study cranial fractures at that time apart from the neurological signs and symptoms, the physical examination of the skull and the surgical examination of the wound, when applicable.

In the second half of the nineteenth century the books of surgery continued discussed the indications of trepanation always around the head trauma. The objective was to recommend which type of head trauma, defined using both lesional and clinical criteria, was suitable for trepanation.

The American surgeon William Thomas Foster from Kansas stated in 1883 the circumstances which require trephining: compound fracture with depression of bone, with or without symptoms of compression; simple fracture with depression and symptoms of compression, after a fair trial of ordinary means; punctured fractures, no matter what may be the condition of the brain; extravasation of blood between the skull and dura mater, or in the arachnoid sac on the cerebral hemispheres; the existence of pus in the same situations; foreign bodies; and, finally, epilepsy and other secondary effects. Following the ancestral recommendation Foster affirmed that the trephine should not be applied to any of the following points: the frontal sinus, the anterior inferior angle of the parietal bone, the course of the longitudinal sinus, the occipital protuberance and the different sutures. He also describes a list of 12 clinical symptoms and signs favouring the diagnosis of cerebral concussion and other list of 12 clinical symptoms and signs favouring the diagnosis of cerebral compression [1].

According to these considerations Terrier and Péraire included a table in his book *'L'operation du trépan'* [2] that gathered the recommendations of trepanation in cranial trauma. In some cases, with no neurological symptoms, they recommended carrying out what they called 'preventive trepanation', particularly for those complete or incomplete skull fractures with foreign bodies or infection signs. They stated that the trepanation was allowed for fractures with fragments that had moved away. Any cranial trauma with immediate neurological signs or with clinical symptoms that appear after a few hours must be trepanned, except for those cases with no wound or depression. Any evolutionary neurological complication is an indication to carry out a trepanation, particularly the infection. Any late symptom, such as epilepsy, paralysis, headaches and mental disorders, is also an indication to carry out a trepanation, whereas sensory disorders do not justify a late trepanation.

Lèon Gallez (1864–1898) made also an exhaustive review of the indications of trepanation in skull fractures in his book *'La trépanation du crâne'* in 1893 [3]. He considered different situations according to its consequences. A 'preventive trepanation' could be carried out in depressed fractures with or without a wound on the pericranium or wounds with foreign bodies, even if there were no brain symptoms. If there were immediate general neurological complications the surgeon was allowed to trepan as long as there was a depressed fracture without a wound. The surgeon must carry out a trepanation if the patient has a wound and both general and focal symptoms. If the neurological manifestations appear within the first hours after the trauma a trepanation would be carried out in those cases with depressed fractures and blood effusions, unless they were intracerebral or intraventricular. Most early secondary complications, such as brain erosion and infection, are an indication to carry out a trepanation. Late secondary complications that required trepanation were epilepsy and paralysis. A trepanation could be carried out if the patient showed sensitivity or mental disorders. The surgeon should not trepan if there were sensory manifestations or a hysteric trauma.

The indications of trepanation only broadened beyond trauma when physicians started diagnosing intracranial lesions at the end of the nineteenth century thanks to the development of topographical localisation of certain neurological functions and symptoms. This forced surgeons to carry out two more things. The first one was to find the projection of these brain regions on the surface of the skull to accurately mark the point to be trepanned. The cranioencephalic topography methods were thus developed as they allowed to know more or less accurately the localisation of the brain regions of interest by using only external cranial references. Surgeons were also forced to make larger cranial openings as they were required to solve the lack of accuracy of the cranioencephalic topography systems, the shift of the brain areas due to the lesion and finally the technical needs to solve the intracranial pathology that required the trepanation. The trepanations were initially enlarged but the definitive solution to this issue was coming and would be the modern craniotomy.

Historically, a few situations of non-traumatic cranial or intracranial lesions had been accepted for trepanation. They were tumours or infections causing local signs and symptoms, such as pain, bulking or swelling that were found by a mere physical examination of the skull. Only in the second half of the nineteenth century neurologists started diagnosing intracranial lesions. This involved an increase in the complexity of the surgery and a challenge for trepanation as the available technique for approaching cranial and intracranial lesions and for their management. We must highlight how soon they started carrying out brain resections without identified lesions to treat post-traumatic epilepsy. At the end of the period that we are now studying different authors were concerned about reviewing these new indications of cranial trepanation for non-traumatic lesions in their books. The inventory of indications became increasingly long and complex.

Antoine Chipault (1866–1920) showed us a general outlook of the surgical indications of cranial trepanation in 1894 [4]. He included within non-traumatic cranial lesions the osteitis caused by metastatic, traumatic, syphilitic and tuberculous osteomyelitis and tumours of the cranial vault. He classified the intracranial lesions topographically according to their depth. He identified those lesions located under the bone (epidural haemorrhage, abscesses and tumours), under the dura mater (such as internal haemorrhagic pachymeningitis that we nowadays call chronic subdural haematoma), on the pia mater and the surface of the brain (haemorrhages, tumours, foreign bodies or abscesses) and inside the brain (infectious lesions such as abscesses, tuberculomas, hydatid cysts or actinomycosis). In addition to this, we must include brain herniations that occurred after the trepanation. He made a thorough compilation of the literature in his book and accurately described 135 cases of intracranial tumours that were surgically treated. Among them, the lesion was not found in 41 cases (30.4% of the cases) and there were 75 cases of cranial tumours that were surgically treated and 9 cases of resection of cortical epileptogenic foci with no macroscopic lesions. He also focused on repairing the cranial defects with osteoplastic techniques. He described 73 cases of repair of a trepanation defect with a *'celluloid heteronecroplasty'*.

Terrier and Péraire described their indications of trepanation for those non-traumatic lesions in their book *'L'operation du trépan'* in 1895 (Terrier and Périer 1895). To do so, they included some simple tables that were supported by their own results and those obtained from literature and which we would nowadays endorse in general terms. The authors recommended trepanning in non-traumatic lesions of the skull, either infections or tumours, as well as for encapsulated or diffuse brain tumours and the *'fungus'* of the dura mater if the lesion could be located by localisation clinical signs. They recommended trepanning for brain abscesses if there was a focal lesion and localisation neurological signs. They recommended carrying out a trepanation with or without cortical resection for non-traumatic Jacksonian epilepsy, whereas they informed that the results were uncertain for *'true epilepsy'*. They did not have the corresponding criteria for many other pathologies, such as brain haemorrhage, meningitis, tuberculous meningitis, microcephaly or mental disorders. They advised that the trepanation in those cases with hydrocephalus was nothing but a part of the *'trepan-puncture'* intervention. They also described the clinical outcomes of short series of trepanations due to intracranial lesions with a mortality rate between a third and a half of the cases.

Lèon Gallez (1864–1898) also presented his indications of trepanations for non-traumatic lesions of the skull and brain in 1893 [3]. He included those skull bone conditions that were due to inflammation (osteitis, caries or necrosis) and tumours (hydatid cyst, exostoses, malignant tumours), brain diseases such as abscesses (idiopathic, tuberculous, actinomycotic abscesses or those derived from an osteitis or an otitis) and tumours (tuberculomas and syphilomas, brain neoplasms), *'fungus'* of the dura mater, brain haemorrhage, hydrocephalus, microcephaly, athetosis, trigeminal neuralgia, epilepsy and finally mental disorders. The author illustrated with clinical cases the different indications and exhaustively reviewed the available literature, describing the clinical outcomes.

It is interesting to observe how soon the indications of trepanation were diversified by pathologies. M. Allen Starr (1854–1932) published the text *'Brain Surgery'* in New York in 1895 [5]. The first chapter was on diagnosis of neurological pathology but it was followed by some chapters on trephination for epilepsy, imbecility due to microcephaly, brain haemorrhage, abscesses, tumours, hydrocephalus and increase of the cranial pressure, mental retardation and cephalalgy. He described 13 of his own cases of surgery for cortical epilepsy.

Regardless of its evolution and the changes of its indications, the trepanation was carried out within a scientific medical atmosphere that was free of any magical element throughout all these centuries. However, there has always been a medicine that was practised in marginal environments where this magical component played an important role, although this was exceptional in the case of trepanation as it was a complex and high-risk intervention. Hence, the trepanation was occasionally recommended for epilepsy and mental disorders since ancient times to evacuate the air, humours or vapours that caused them. The trepanation was recommended for melancholy during the seventeenth and eighteenth centuries. As we have seen, it was still carried out to treat post-traumatic epilepsy at the end of the nineteenth century. However, it was then used to resect sclerosed or cicatricial cortical epileptogenic foci.

22.2 The Cure of Folly

An extreme example of indication of cranial surgery was the extraction of a stone from the head (*'The Cure of Folly'* in English; *'La piedra de la locura'* in Spanish; *'Het snijden van den Kei'* in Dutch; *'La pierre de tête'* or *'La pierre de folie'* in French; *'Der Steinschneider'* in German). This practice was only documented in a short series of paintings from Flemish painters from the Netherlands that were mainly painted between the sixteenth and seventeenth centuries. The first painting about this topic was the table *'The Extraction of the Stone of Madness'* by Hieronymus Van Aeken Bosch (Madrid, Museo Nacional del Prado, c. 1501–1505). It was the only medieval painting of the series that laid the foundations for the others that were painted in the Flemish Region during the sixteenth and seventeenth centuries, such as those by Jan Sanders van Hemessen (*'The Surgeon'*, 1550, Madrid, Museo Nacional del Prado), Pieter Bruegel el Viejo (*'Cutting out the Stone of Madness'*, 1550), Pieter Huys ('*A Surgeon extracting the Stone of Folly'*, 1561) or Jan Steen (*'Cutting the Stone'*, 1670). The image was the same in all the paintings. There is a surgeon making an incision of the patient's forehead, from where he extracts a stone. There are other characters around them observing or commenting the intervention. The relationship between mental disorders and stones comes from an ancient belief that stated that the brain, just like other organs such as renal pelvis or gallbladder, could make stones. Old stories say that these stones had been found in autopsies and were the cause of the madness of these patients. This information, which was completely wrong, justified this intervention, which required an authentic trepanation to extract the stone. Hence, the Persian physician Rhazes (854–925) had already reported that there were quacks who healed patients from epilepsy by making an incision on the forehead and pretending to extract a stone from the head. Others pointed out that the cranial incision would be useful in patients who suffered from excruciating headaches or migraines as it produced a sensitive input that counteracted the acute pain, according to the modern gate control theory proposed in 1965 by Melzack and Wall. According to other authors the intervention was carried out by barbers or quacks who operated fraudulently as they knew it was a trickery and kept the stones hidden in their hands to earn money. The eventual benefit of the intervention would be similar to a placebo. Hieronymus Bosch's painting has an inscription which reads as follows: '*Meester snyt die Keye ras, myne name is lubbert das*'. It means 'Master, remove the stone from me, my name is Lubber Das'. Lubber Das was a satirical character in Dutch literature which represented the stupidity [6, 7].

However, the exhaustive documentary studies that have been conducted about the surgical activity carried out by Flemish physicians, surgeons, barbers and quacks have not allowed to find any document of that time or from a previous one that gathered, described or certified this practice. Therefore, we cannot even affirm that it was really carried out apart from what is shown in the paintings. The supporters of this theory affirmed that as there were no documents that proved the practice and basing on the scenography analysis of the paintings, the images that show it must be interpreted as allegorical, moral or theatrical scenes. The extraction of the stone of madness was never carried out.

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23 'State of the Art' of the Cranial Opening in the Second Half of the Nineteenth Century

23.1 'State of the Art' of the Cranial Opening

There was an incredible advance concerning all fields of industry, technology and science, and thus medicine at the end of the nineteenth century. A series of revolutionary technical innovations were introduced in surgery in just a few years, such as surgical general anaesthesia with ether and chloroform and local anaesthesia with cocaine and other local anaesthetics, effective surgical haemostasis that improved the classical cauterisation and the tourniquet with the use of surgical ligations and haemostatic forceps, transfusion and serotherapy and finally the antiseptic techniques with carbolic sprays and the later aseptic techniques with the sterilisation of surgical material, hand washing or use of gloves and masks. The industrialisation improved and the design and manufacturing of surgical instruments were diversified. Finally, medical and surgical specialties were created.

The number of major surgical interventions carried out at hospitals was not particularly high at the middle of the nineteenth century. The amount increased only thanks to the implementation of these revolutionary advances. Hence, an average of only 39 interventions per year were carried out at the Massachusetts General Hospital between 1836 and 1846. After the anaesthesia was introduced in 1847, the annual average increased to 189 interventions. Finally, the number of surgical procedures increased to an average of 2427 annual interventions between 1894 and 1904 after the aseptic and antiseptic techniques were introduced. It even reached 4000 surgical interventions in 1914.

The trepanation technique was also influenced by these developments. In addition, intracranial lesions could be topographically localised before surgery. Therefore, some surgeons started carrying out trepanations in non-traumatic cases in France. Paul Broca (1824–1880) was the first one who carried out a trepanation guided by clinical data and craniometric localisation of cortical structures. Paul Broca predicted indeed that a patient with aphasia had a lesion on the 'third left ascending frontal gyrus' and he found it on the 27th of July of 1871 by a trepanation.

In addition to the medical improvements, we must highlight how quickly the technical developments of that time were applied to trepanation and cranial surgery. An example of this was the quick use of electricity as a motor power for the trepanation systems, particularly bone saws at first, as well as for the localisation of brain areas by direct electric stimulation of the brain cortex with faradaic current. Many of these developments will be explained in the next chapters.

We are now going to explain the situation of the cranial opening technique and its advances during the last third of the nineteenth century through the papers and books of some eminent surgeons of that time. In terms of documentary evidence, we

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luckily have a great amount of information from medical texts, clinical and surgical records from hospitals, surgical instruments that are well preserved, anatomical pieces, catalogues, news and even photographs. This has even allowed to make fictitious recreations of trepanation interventions in films and television series with some plausibility. There is a particularly interesting series about the fictional activity of the Knickerbocker Hospital in New York at the end of the nineteenth century (*'The Nick'*). The main character, Dr. John Thackery, played by Clive Owen, which is inspired in turn by the figure of William Stewart Halsted, carries out a trepanation to place a ventricular drain and operate a brain tumour. He also carries out a cortical resection to treat an addiction to morphine where he uses a cortical electrical stimulation system. Real instruments of that time are used for these and many other interventions that are shown in the series, which reliably reproduces the operating room and the activities and rooms of the modern hospital from the end of the nineteenth century. Physicians and surgeons were universally trained in medical schools in that time. There were also surgery training programs in large hospitals and the information exchange was allowed by means of journals, conferences and visits.

23.2 Two Great French Surgeons at That Time: Terrier and Chipault

We are going to describe the situation of trepanation in France at the end of the nineteenth century. France was the country where this technique achieved its highest degree of development and technical sophistication, which also affected surgical instruments.

Félix Terrier (1837–1908) was a great French surgeon who was born in Paris. He promoted the antiseptic techniques and proposed, along with O. Terrillon, two methods to make surgical instruments aseptic (boiling and autoclave) in 1883. He wrote the book *'L'operation du trépan'* along with M. Péraire in 1895 [1]. We are going to follow this work to describe how the trepanation was carried out in that time. F. Terrier and M. Péraire recommended trepanning both for traumatic and non-traumatic lesions. However, the former was still more frequent and they analysed them in detail.

The authors introduced elements that we can consider modern along with others that were clearly ancient in the trepanation technique. The patient's skull was shaved and disinfected 1 or 2 days before the intervention, leaving it covered with an antiseptic dressing until the moment of the intervention. The place of the trepanation was marked on the skin using cranial references. The patient was anaesthetised with ether or preferably chloroform. Any painkiller such as morphine, vasoconstrictor medicines such as ergotamine or local anaesthetics such as cocaine could also be used. The head was disinfected and it was placed on a sand bag so that it was fixed. The skin incision was made with a scalpel and had crescent, V, T or even better a horseshoe shape. They completely rejected the classical cross-shaped incision. They carried out ligations or used forceps to achieve the haemostasis of arteries and the skull was denuded. The cranial opening itself could be carried out with the trepan, the trephine, the chisel and the mallet or Heine's *'osteotome'*.

However, Terrier and Péraire preferred trepanning with the *'trépan à couronne'*. They described the instrument under the generic name of *'trépan'*, which had a brace handle and a hollow truncated cone-shaped crown driller with a grooved external surface and a central pin. They pointed out that a mark was made on the bone exactly where they were going to trepan and the pin was placed there. The pin protruded half centimetre from the crown. The brace was rotated by exerting a perpendicular pressure on the skull. They rejected the chin or frontal support due to aseptic reasons. The perforation was slowly and carefully carried out. They repeatedly lifted the instrument to clean the bone sawdust with a sterilised brush. They checked with a probe that the pin had finally drilled the internal table. The hole made by the pin was used then to introduce a *'tirefond'* and lift the disc of the internal table. The drilling crown could not dip due to its truncated cone shape (*'le trépan étant ainsi* *insummersible, abaptiste.'*). The margins of the osseous opening were harmonised with a lenticular knife or a *'rugine'*. The size of the crown was variable, depending on their needs. According to different authors they could have between 22 and 50 mm although the large ones were difficult to use. Several consecutive holes could be made to enlarge the cranial opening or use the saw and the chisel between them if the drills were separated.

The dura mater could be opened if it was necessary. If so, he recommended making a horseshoe incision 5 mm from the osseous margin and folding it over the closest dural venous sinus. Examining the brain included assessing its colour, its herniation or tendency to herniation and its modifications concerning its consistency, in this case using *'un doigt parfaitement aseptisé'*. The intracerebral examination could be carried out by a puncture, incisions made with a scalpel or removal of gyri. He recommended using drain freely and suturing the dura mater and the pericranium. Finally, they discussed about the options concerning the repair of the cranial defect created by the trepanation over many and many pages. They included either the replacement of the resected disc of bone, or autoplasties with bone obtained from the same skull, heteroplasties with animal bone, desiccated bone or sheets made of cork, rubber, leather, gutta-percha or metal (silver or aluminium).

Another great French surgeon involved in the development of the trepanation technique at the end of the nineteenth century was Antoine Chipault (1866–1920). He was born in Orleans and is considered the father of French neurosurgery. He had a discreet and dark personal life. He retired from his social and professional life at the age of 39 as he was affected by an undetermined neurological disease that caused him a tetraplegia. He published *'Études de chirurgie médullaire'* and *'Chirurgie opératoire du système nerveux'* in 1894 and *'Chirurgie nerveuse d'urgence'* in 1904 [2, 3]. He was a disciple of Terrier. For this reason, his work *'Chirurgie opératoire du système nerveux'* reproduced many concepts, texts and illustrations from his master, with a few technical innovations concerning the previously mentioned issues. Some interesting aspects made the difference between both surgeons, even though they were separated just by one generation.

Chipault took the importance of aseptic and antiseptic techniques for granted. For this reason, he did not focus a lot on this issue. However, he was concerned about the intraoperative and postoperative mortality due to the surgical shock. His review included 802 brain surgical interventions. Among them, he estimated a mortality due to the shock of 1.6% in surgical interventions of the anterior area of the brain, of 7.5% in interventions of the convexity of midbrain, of 21.6% in interventions of the skull base and of 35.1% in surgical interventions of the cerebellum.

Just like his master Terrier, he gave a lot of importance to cranioencephalic topography. He gathered and systematically described the craniometric and cranioencephalic topography methods that were known and used to localise cranial and brain anatomical structures in his work. He also developed and described a great amount of original methods. He gave so much importance to cranioencephalic topography that he classified neurosurgical lesions into those that were solved with direct cranial resections (such as cranial fractures and cranial lesions) and those intracranial lesions that required to modify the previous basic procedure using topographical localisation techniques because the lesion was not visible (trauma, osteitis and tumours). Apart from this, he considered those lesions in the skull base, which required a special trepanning technique and a particular cranioencephalic topography, especially concerning the localisation of dural venous sinuses. He included within this last group those lesions affecting the paranasal sinuses, mastoid, pars petrosa and abscesses of the cerebellum. He finally wrote a chapter on the specific surgical techniques for treating the microcephaly, hydrocephalus and encephalocele.

Chipault supported the horseshoe-shaped incision, with a design based on the anatomical considerations of the vascular supply and innervation. To carry out the cranial perforation he vindicated the use of the brace-handle trepan with a hollow truncated cone-shaped crown and a central support pin that was characteristic of the French school (*'le trépan a couronne et* *point d'appui central, preque toujours modèle Bichat'*). As an alternative, he briefly mentioned *'la tréphine dite Anglaise'* with a crown mounted on a T-handle which was used similar to a corkscrew. However, he pointed out that it might have a ratchet-like mechanism to make the job easier for the surgeon.

He then described different techniques for enlarging the initial window to make openings with a big size and a variable shape. He did not recommend using crowns with a large diameter to achieve large windows as there was a high risk of injuring the dura mater. He suggested using 1-in. crowns, i.e. 26 mm of diameter, and then enlarging the initial hole. This enlarging process could be gradual by resecting bone with gouge-like bone forceps, a chisel and a mallet or different types of saws. A new consecutive burr hole that was secant to the previous one could also be made. To do so, he used the forceps that Farabeuf had specifically designed for this purpose as they allowed doing it without injuring the dura mater. By gathering several secant burr holes he could achieve resections of all kinds of shape and size. For example, three burr holes made a clover-shaped triangular hole, whereas four burr holes made an almost square opening, whose sides could be harmonised. The third way of enlarging the initial hole was making one or more burr holes away from the initial one to resect then the bone that was between them. Another interesting technical innovation was recommending a wax putty to plug the bleeding of the diploe.

Concerning the cranial opening technique Chipault was an example of a great surgeon who experienced a paradigm shift on the approach to intracranial lesions. When he described the cranial resection procedures he summed up those ones he had a personal experience in. He later selected those ones that he considered to be really useful. The techniques he experienced were the following: cranial resection with the trepan ('the most ancient known by surgeons'); cranial resection with a saw that was either a straight handsaw or a circular saw driven by a crank, drill, pedal or connected to electricity; cranial resection with bone-cutting forceps; cranial resection with compass (a procedure suggested by Paré which was carried out with other instruments in that time); and finally cranial resection with two instruments (one for drilling and the other for enlarging the drill). The last one was the most frequent procedure used by Chipault. He made the initial drill with a trepan and enlarged it by punching it with gouge forceps or by creating a groove with bone-cutting forceps, a chisel or a Toison band saw.

Chipault, according to the personal experience he had acquired with all these procedures, selected the two following 'until further notice'. When he wanted to carry out a definitive cranial resection in the vault and suboccipital areas he made an initial resection with the trepan and enlarged it with gouge forceps or with Farabeuf's trepan-forceps. On the contrary, when he considered it was feasible and useful to carry out a temporary bone resection at a brain level, which was unusual for the author, he carried out a personal version of the temporary osteoplastic craniotomy that had been described by Wilhelm Wagner (1848–1900) a few years before, in 1889. Chipault called his opening a *'trépanation bilinéaire avec travée autoplastique intermédiaire'*. Both techniques will be described in detail in the next chapters, when reviewing the origins of modern craniotomy.

23.3 Other Relevant Surgeons

Jean Marc Bourgery (1797–1849) wrote a monumental book entitled *'Traité complet de l'anatomie de l'homme'*. The book has nine volumes and was published over several years, between [4], by Jean Marc Bourgery and Claude Bernard and the professor, draftsman and anatomist, N.H. Jacob, with the help of Ludovic Hirschfeld. It is a book of anatomy and topographical surgical anatomy that contains at the end of each volume a number of plates with representation of the surgical techniques and the necessary instruments (Fig. 23.1). Plate 53 refers to the *'Trépanation des os du crane et instruments du trépan'* and in an accompanying text the instruments and the surgical technique are explained. The instruments are as follows: Fig. 1. Trepan mounted with all its accessories. It consists of the handle (a) with a

Fig. 23.1 Instruments for trepanation and surgical technique of and enlarged trepanation as described by Jean Marc Bourgery (Bourgery JM. Traité complet de l'anatomie de l'homme. Tome sixième. Paris: Chez L. Guérin; 1866–1871)

widened and slightly concave end or plate (b) on which rests the forehead or chin, and the other that mounts the crown (c) inserted in a shroud and held by a spring (d). Figs. 2, 2bis, 3 and 3bis. Spare crowns of different diameters without and with the pyramid. Figs. 4. Pyramid. Fig. 5. Key for the pyramid. Figs. 6 and 7. Piercing, triangular and brace trepans. Fig. 8. *'Tire-fonds'*. Figs. 9, 9bis, 10 and 10bis. *'Rugines'* and different tips. Figs. 11 and 12. Single- and double-lenticular knife. Fig. 13. Cleaning brush. Figs. 14 and 15. Elevators to lift the bone discs serrated by the crown. Fig. 16. *'Elévatoire-rugine'*. Fig. 17. *'Tréphine (ou trépan anglais')'*. This instrument is no more than another hand-operated trepan with a transverse grip. The accessories of the main instrument are the same. In the crown is fitted a slide of M. Charrière (17bis), which rises and falls at will in a slot that mounts a screw under pressure and serves to limit the depth of cut of the crown.

Operation of cranial trepanation is also beautifully drawn and precisely described. There are three figures in the lower part of the illustration showing the steps of surgery from the eye view of the surgeon. The first one shows that the patient, in a coma, is lying down and the head is supported in a way that offers the surgeon the left surface of the head. The hair has been shaved. A cross incision exposes a large frontoparietal surface. Four holes have been made with a crown of trephine, and have been raised. The surgeon is busy making a fifth crown *'of manière à pratiquer une large ouverture'*, as is necessary to expose a diffuse effusion on the surface of the cerebral hemispheres as it occurs in skull fractures. The figure highlights the following: (a) The left hand of the surgeon who keeps the plate circularly between the thumb and forefinger; (b) plate on which the surgeon supports the forehead or chin; (c) fingers of the right hand that handle the central ball of the handle in a circular motion; (d) surface of the dura mater. In the second figure other phases of the operation are represented. (e) Right hand of the surgeon regularising the edge with a lenticular knife; (f) section with the incisive clamp of the angles of bone of the concave edges that leave between them the crowns of the trepan. This action helps increase the size of the opening. Finally, the last figure shows the section of the dura with a straight scalpel, in the case quite necessary to release the blood or pus accumulated on the brain surface.

Later, the proposal of the theory of brain localisations develops the interest of surgeons to approach the motor cortical centres using craniometric techniques. In this sense, the technique of trepanation described by Victor Chalot (1850–1903) in 1886 in his book of general surgical technique *'Nouveaux éléments de chirugie opératoire'* is interesting [5]. Chalot made a small square trepanation using a chisel or a trepanation in the highest portion of the Rolando fissure or central sulcus, with the cutaneous flap turned medially with a hook. To enlarge the approach carried out a double trepanation. The second hole is practised in the form of 'number eight', with a scalp flap designed particularly for himself (Fig. 23.2).

Meanwhile, on the other side of the scientific world, in the United States of North America, Allen Starr (1854–1932), a neurology professor at Columbia, published the first text on cranial surgery written by an American, although he had been trained in Europe. The text was titled *'Brain Surgery'* and it was published in New York in 1895 [6]. He described the trepanation technique (*'trephining'*) in the last chapter. He had already

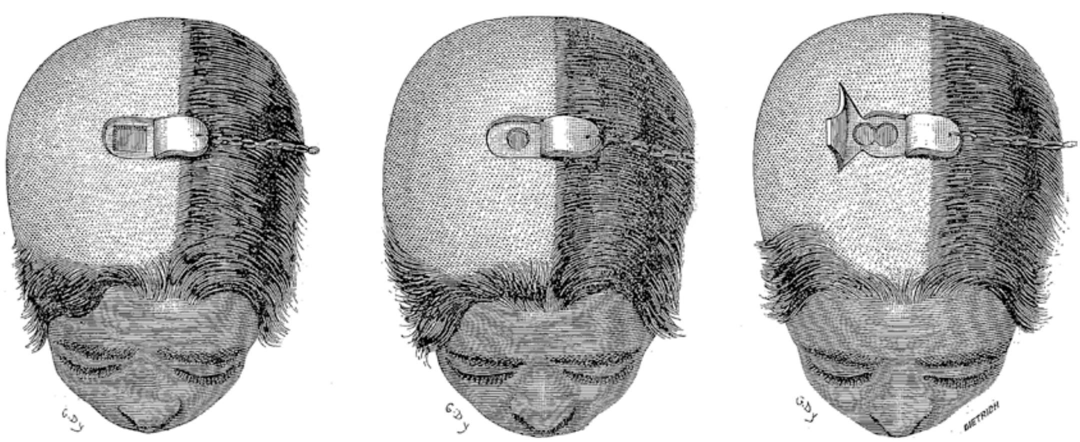

Fig. 23.2 Surgical technique of trepanation by Victor Chalot (Chalot V. Nouveaux éléments de chirugie opératoire. Paris: Octave Doin; 1886)

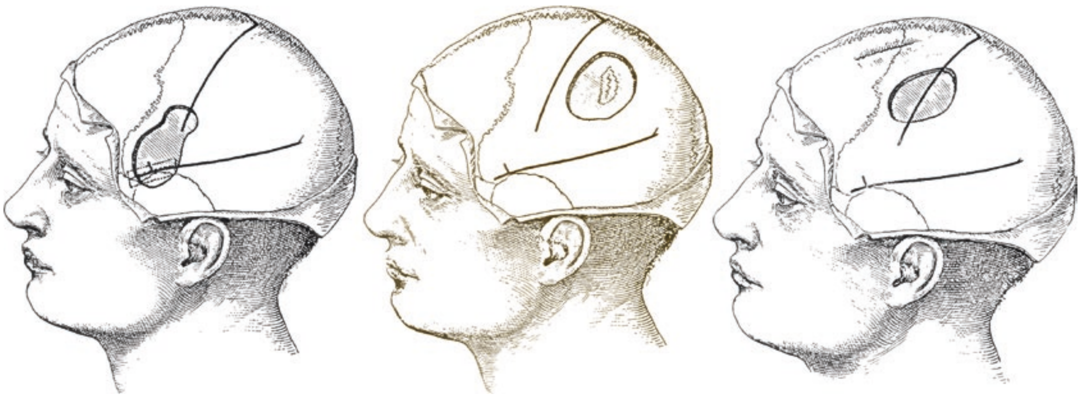

Fig. 23.3 Different types of enlarged trephines made by Allen Starr for resection of cortical epileptogenic areas (Starr A. Brain Surgery. New York: William Wood & Co; 1895)

watched this surgical procedure many times and in many different ways. Starr started the opening with a trephine of at least 1 ½ in. He pointed out that other surgeons started with a trephine of ¼ in. to enlarge the hole with gouge forceps. Another alternative option was to make two close trephines and resect the bone between them with gouge forceps, a chisel and a mallet or an electric circular saw. The author accurately described 13 of his own cases of cortical epilepsy surgery that were treated with trephines. He drew the trepanation of each case, which gives us an idea about the place, shape and size of the trepanations of that time (Fig. 23.3).

23.4 Comments

As it can be observed, the cranial opening made with the trephine was not enough to solve most of the intracranial lesions at the end of the century. Surgeons needed larger cranial openings. Reports of cases of remarkable operations can be found in the medical literature of that time, where it is described that patients were trephined several times in the same surgical procedure or along successive procedures. Guthrie required 12 perforations to render the elevation of a depressed bone fracture and Shumacker relates the case of patient where the operation was performed 11 times in less than a month, in both cases with a remarkable good result. Phillip, Count of Nassau, fractured his skull in several places by a fall from his horse; he was trephined 27 times by Henry Chadborn, a surgeon of Neomagen, to whom, after his recovery, he gave a certificate as a proof of skill [7].

The limitations of the current surgical instruments and techniques to solve the most routine cases are clearly demonstrated in this case report described by JF Horne in 1894. In this real case of a depressed fracture of the skull, Horne explains the use of several instruments in the same operation, namely, the trephine, an elevator and a Hey's saw [8]. The description of the surgery, carried out on February 17, 1882, is textually as follows: 'At 11 a.m., my assistant (Mr. Hall) gave chloroform. Then lengthened the wound in the scalp at both ends. The depression was formed by the driving in of the outer table to the extent of two inches in length, and varying from one to half-an-inch in breadth. A small trephine was now applied; and then, by means of Wheelhouse's elevator, the outer table was easily removed. The fracture of the inner table was much greater in extent and comminuted. Here I must state, in prizing up one of the fragments with a small elevator, it, much to my annoyance, slipped off the fragment and penetrated the membranes of the brain. The bleeding became profuse; the loose pieces of the inner table of the skull were removed, and sharp corners of the bone cleared away by Hey's saw. I was unable to get at the cause of the bleeding, which was evidently venous, the blood welling up in the wound each time I removed the sponge, the brain pulsating through the wound in the membranes. The scalp was laid over the wound—no sutures were put in—and covered with lint soaked in carbolic oil, a large pad of lint over this, and pressure applied by means of a bandage, and the patient removed to bed'.

For this reason, surgeons developed the techniques for enlarging the trephine that have already been described and that presaged the invention of modern craniotomy and the final death of the trepanation as done along centuries.

The long period of time that has been discussed in the last chapters covers from the middle of the sixteenth century to the end of the nineteenth century, that is, the Renaissance, Enlightenment, and First and Second Industrial Revolution periods. Medicine became increasingly scientific, but the advances were accompanied by a high degree of empiricism. The great ancient anatomical barriers of trepanation were little by little overcome and abandoned and surgeons started trepanning on sutures, dural sinuses or posterior fossa. The indications of trepanation were still focused on cranial traumas and fractures. At the beginning of the nineteenth century it was already clear that surgeons had to distinguish between the bone fracture and the clinical symptoms derived from the trauma. They already knew that the trepanation should be recommended considering the neurological manifestations. However, the schools (particularly the British one) showed a lot of opposition, as they recommended trepanning indiscriminately any cranial trauma. The criticism arose when considering the high mortality of trepanation and as they could not identify whether this mortality was due to the trepanation itself or the trauma for decades. However, the major cause was the infection. It is noteworthy to mention that the technical development and the advances of the trepanation technique were very slow during these centuries. Many re-inventions and minimal variations of the instruments and techniques were developed.

Luckily, a series of events took place at the end of the nineteenth century. They solved that situation and promoted new developments. The introduction of aseptic and antiseptic techniques allowed to control the mortality rates. The instruments were adapted to the sterilisation needs. The trepanations were carried out at hospitals and the techniques and results were systematised, assessed, verified and exchanged. Clinical neurology was able to diagnose and localise intracranial lesions apart from traumatic lesions and their complications. Therefore, surgeons dared to surgically treat them. Enlarged trepanations did not meet these needs. Hence, modern craniotomy was developed along with neurosurgery as a surgical specialty.

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24 Trepanation and Trephine in Modern Age: Illustrative Cases

Cases of trepanation for discussion can be collected from historical records or from the medical texts. The chronicles from the Middle Ages and the historical documents frequently of that time describe cases of cranial injuries and trepanations in relevant people from the court, noblemen or members of the royal families, such as Lorenzo de Medici in Italy, king Henry II of France or prince Carlos of Spain. However, texts of the medical literature from the seventeenth century described many clinical cases. These case reports were increasingly frequent in the medical literature of the eighteenth and nineteenth centuries. The cases allowed to show the reader the recommendations suggested by the author. They also provided theories, classifications or lines of action. These descriptions were particularly numerous and accurate in some texts. They show how the surgeons of that time struggled to solve their patients' problems and the fight against the disease with no diagnostic methods in that time and battling an unknown enemy (bacterial infection).

Historical literature of trepanation has given much importance to the case of Friedrich Bachmann. He was a German dealer who was involved in a traffic accident with his carriage on the road from Strasbourg to Frankfurt/Main. He was treated by Lorenz Heister (1683–1758) as he probably suffered from a chronic subdural haematoma. The case was accurately described by Heister and can be easily read in the English translation *'A general system of surgery'* of his book *'Chirugia'*, which was written in Latin [1]. Recently, Ruisinger brilliantly described and contextualised the historical, medical and social aspects. It is a good example of this kind of studies. For this reason, we are not going to use it.

Daniel Turner (1667–1741) published a particularly detailed clinical case in the monograph *'A remarkable case in surgery: wherein an account is given of an uncommon fracture and depression of the skull, in a child about six years old; Acompained with a large abcess or aposteme upon the brain. With other practical observations and useful reflections thereupon the brain. Also an exact draught of the case, annex'd. And for the entertainment of the senior, but instruction of the junior practitioners. Communicated'*, which was published in London in 1709. The long title of the work has to do with the detailed description of the case over more than 50 pages. It includes the treatment that the patient underwent for 3 months and several interventions that were fruitless as he finally died. The monograph has a print that shows a drawing of a child's injury on the skull, the trephination that was carried out and the bone fragments that were lifted. Turner also described the results of the autopsy of the child that he carried out himself a day after his death [2].

Medical texts about war surgery accumulate also a great number of case reports and some of them have been presented and discussed in the chapter devoted to trepanation in war times. Among the

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thousands of illustrative cases that affected anonymous patients and that were well described in the medical books that we have reviewed, we have selected some of them that we are now going to describe and comment along with a fictitious case from a famous novel and film.

24.1 Brain Hydatid Cyst

Each chapter of the book *'Chirugie opératoire du Système Nerveux'*, which was published by Antoine Chipault (1866–1920) in [3], includes a list of bibliographic references at the end followed by some statistical tables with the cases described in the literature. Each case provides information in five columns about the author and bibliographic reference; the age, sex and symptoms of the patient; type of tumour; intervention; whether the tumour was found or not in the surgery; and finally the therapeutic outcomes. As for the table of intracranial tumours that were surgically treated, he gathered and described 135 cases that had been published. Among them we have selected a case of brain hydatidosis that was treated by Dr. Chisholm and which was published in the Australasian Medical Gazette in 1893.

It was about a 12-year-old adolescent, who suffered from crisis of paresis on his right side of the body that was aggravated after feverish conditions since he was 6. He related he had headaches and hypersensitivity on the left side of his skull. An ocular fundus exam showed bilateral optic neuritis (papilledema). A trephine hole of ¾ in. was carried out on the left side 1 in. from the middle line and 1 in. ahead the coronal suture. Once the disc of bone was removed the dura mater was herniated through the hole without showing pulsations. It was punctured with a fine hypodermic needle. A rubber tube was placed to drain 3 drachms (1 drachm = 3.7 cc) of liquid, one drop after another. The manoeuvre was facilitated by bending the operating table. The tube was removed and the cyst was directly punctured. Then, 10 and ½ ounces of liquid were evacuated in half an hour. They tried to remove the capsule of the cyst with a pair of forceps but it was fragmented. They poured a boric acid solution in the cavity to sterilise the cyst. Finally, they obtained a cavity of about 4 in. The dura mater was closed with catgut and the skin was sutured with silk and horsehair. The clinical evolution of the patient was negative; he had high fever and finally deceased.

We are discussing a case of a frontal trepanation to treat a hydatid cyst, which was very frequent in that time and in that geographical area. The diagnosis and the treatment correspond to the surgical *'state of the art'* of that time. The great amount of liquid that was drained suggests that a lateral ventricle might have been punctured. It is impossible to distinguish at first sight the liquid of the hydatid cyst from the cerebrospinal fluid. The clinical outcomes were tragic and there was no clinical information apart from the fever. We do not even know the post-operative evolution time. This is an example of how the cranial trepanation became a mere approach to intracranial lesions that were previously diagnosed and localised with clinical and craniometric methods. Brain hydatid cysts are nowadays exceptional in those countries with developed healthcare and animal health systems. However, it still exists in underdeveloped countries. It was a pretty common disease in the American Southern Cone at the beginning of the last century. There was a burgeoning neurosurgical activity in that area. Brain cysts were treated with large craniotomies in that time. The cyst was removed without emptying or breaking it to avoid contaminating the brain with the liquid of the cyst that was full of scoleces. To do so, a corticectomy was carried out. The wall of the cyst was exposed and it was forced to exit due to the intracranial pressure itself or by increasing such pressure by carefully injecting saline fluid on the lumbar region or in the plane between the cyst and the brain. This procedure was called 'cyst labour'.

24.2 Brain Tumour in Right Motor Cortex

We are now going to describe a second case that was included in the previously mentioned table created by Antoine Chipault (1866–1920). This case was about a brain tumour (small round-cell sarcoma) that was treated by Dr. Gleghorn and which was presented at the Intercolonial Medical Congress of Australasia in 1892.

The patient was a 26-year-old woman with epilepsy who underwent four trephinations on the convolution of Rolando (precentral gyrus). The dura mater was taut and showed no pulsations. It was opened by a cross-shaped incision. The subcortical lesion was found with a needle and it was reached with a pair of forceps and with the fingers, removing the necrotic brain tissue and washing the cavity with warm water. The dura mater was closed, leaving an opening that matched one of the trephine holes. The other three discs of bone were placed back to their original position. The results of the surgery were irrelevant as the facial epileptic crisis on the left side persisted and the hypoesthesia on the left side of the body turned into an anaesthesia. A brain herniation appeared 8 days later. It caused a transitory left hemiplegia when it was compressed with the bandages. The patient underwent surgery again 2½ months after the first intervention. The bone discs that were left were well integrated. The herniation was removed by ligating it with catgut. The stump was re-introduced with the finger inside the cranial cavity. The dura mater was reinforced with a flap. The local and neurological symptoms improved. The patient underwent surgery again 4 months later. A new trepanation (a large one this time) was carried out ahead of the previous openings. The sagittal sinus was ripped during the approach. The abundant venous bleeding was controlled by compressing with a sponge. Another trephination was carried out. The dura mater was opened again. It was punctured and the tumour tissue was resected. The patient experienced again a transitory improvement.

The patient probably suffered from a high-grade glial tumour that had developed from a low-grade lesion located in the frontal region. The gyrus of Rolando corresponds with the motor area. There were many craniometric methods that were described in that time to localise it, as it was under the parietal bone. However, the tumour probably pushed the gyrus backwards. The only available method in that time was localising the subcortical tumour by puncture and the only treatment was a cortectomy and resection with forceps or with the fingers. It is noteworthy that one bone disc was not placed back to its original position in order to achieve a decompression. From a clinical perspective, it was ineffective as a brain herniation soon appeared and forced the patient to undergo surgery again. The negative evolution led to third surgical intervention with a new large bone resection that was anterior to the previous one. The craniotomy was accompanied by a serious intraoperative complication which was ripping the superior sagittal sinus. It was controlled by compressing with a sponge. The exclusion of the superior sagittal sinus on its anterior third usually has no neurological consequences. Part of the tumour was again resected in the third intervention. The bone was not replaced so the patient's condition depended on its evolution. This case clearly illustrates the diagnostic, technical and technological level of a remote colony such as Australia at the end of the nineteenth century. It took place in a moment that was almost contemporary to the introduction of the osteoplastic craniotomy with pedicle flap.

24.3 Brain Abscess

We describe now a Goldstein case that was included in the book *'La trépanation du crâne'* by Lèon Gallez (1864–1898). It is an example of the topographical diagnosis and the therapeutic possibilities that surgeons had at the end of the nineteenth century.

33-year-old male: Medical history: gastric fever 5 years before, later melancholy with mystical delirium, painful cervical swelling that disappeared when massaging with mercury 3 years later. Then he experienced headaches once a week. He was treated of a trigeminal neuralgia. The brain compression symptoms started on the 7th of January of 1888. The examination carried out on the 20th of January showed the following: speech troubles but without aphasia; headache on the right side that increased in a certain point located above the ear, in the parietal region; paresis of the left leg and also in the arm (but less pronounced); normal sensitivity; no fever;

regular breathing; bradycardia of 32–40 bpm; bilateral papilledema; and dilated right pupil. The intelligence was soon altered and the paresis was substituted by a paralysis. The patient showed a total somnolence on the 21st of January.

A trepanation was carried out on the point that hurt when pressing it. The dura mater was bluish and taut. After making an incision on it some greenish purulent material came out along with decaying brain matter. The brain around it was removed. The intervention led to a significant but short-term improvement. The patient passed away 4 months later due to a meningitis.

The patient was suffering from a condition with endocranial hypertension that was clearly focused on the right hemisphere. The evolution of the patient was very quick. It was all characteristic of a brain abscess. The patient fell into a deep coma 24 h after the examination, which suggested a transtentorial brain herniation. The available medical background did not help them to determine the cause of the infection. The trepanation was carried out on the selective point that hurt when pressing it according to the surgical criteria of that time. An incision on the dura mater and the brain cortex allowed to evacuate the pus with brain matter. This suggests that the abscess was at a cerebritis stage, with no signs of encapsulation. The neurological improvement was due to the decrease of the intracranial pressure. However, it was transitory as the infection persisted and the patient deceased.

Nowadays the abscess would have been diagnosed and localised with imaging studies. In a clinical situation similar to the one this patient experienced the abscess would have been drained to reduce the intracranial pressure and obtain material for a bacteriological study. The place of the trepanation would have been based on the imaging studies, probably with the help of neuronavigation. The aim of surgery in abscesses with capsule can be a complete resection of the lesion by means of a craniotomy, whereas no surgical treatment is recommended for those abscesses at cerebritis stage. Surgery is only recommended during the pseudo-capsule stage to control the endocranial hypertension and obtain material for culture. This can be achieved through a trepan or trephine hole. Nowadays the patient described would have been given ventilatory and haemodynamic support along with an initial empirical antibiotic therapy that would be later adapted according to the bacteriological results and the antibiogram. For this reason, the survival probabilities would have increased. However, the mortality of brain abscesses is still significant.

24.4 Fictitious Case: Trepanation Showed in the Film 'Master and Commander'

The film *'Master and Commander. The far side of the world'* is about the epic story of the British frigate Surprise and its tough battle against the French frigate Acheron. It took place in the Pacific Ocean in 1805 during the Napoleonic Wars. It is also about the extraordinary friendship between the commander of the ship (Capt. Jack Aubrey played by Russell Crowe) and their physician (Dr. Stephen Maturin played by Paul Bettany), a science man of that time of the Age of Enlightenment who was very interested in botany and biology. The hard lives of the sailors and the conditions in the vessels are vividly shown. The film, which was directed by Peter Weir and released in 2003, changed the historic scenario of Patrick O'Brian's novel, which took place in the American Civil War. A trepanation is described and showed in the film.

The sailor Joe Plaice, an aged man, has an accident when he is hit on the head with a metal piece and falls from the stairs. He breaks his skull bone and is diagnosed with a depressed cranial fracture that has a terrible prognosis. The intervention is recommended due to the negative evolution of the patient. It is carried out on the deck of the vessel, in front of all the crew. A cross-shaped incision is carried out, along with a cranial drill with a trephine that has a T-handle. A disc of bone is lifted. A 3-shilling coin is used to fill the osseous defect after the trepanation. A Galen's bandage is applied. The evolution of the patient is quickly satisfactory in all aspects.

Some depressed fractures are recommended to be surgically treated. The scenes about the trepanation of the sailor include authentic elements that are characteristic of trepanations of that time, such as the lack of anaesthesia, carrying out the intervention outdoors to have more light, presence of people around, cross-shaped incision or use of a crown trephine with a T-handle. The cranioplasty with a coin was not carried out at that time. It might be a free interpretation of the use of metal sheets that were externally applied on the osseous defects or brain herniations that resulted from a trepanation.

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Part VI

Modern Times. History of the Craniotomy

Des deux méthodes: trépanation, craniectomie, la dernière est à tous points de vue supérieure;… . C'est la méthode de choix, qui tend à se substituer peu à peu à la première

George Marion (1869–1960)

25 Wilhelm Wagner's (1848–1900) Temporary Cranial Resection and Its Initial Improvements

The historical period covered by these following chapters is pretty short, a little longer than a hundred years, from the end of the nineteenth century to nowadays. The changes and innovations of the techniques in craniotomy, just like in other field of science and technology of this period of time, have been increasingly faster. For this reason, when describing the historical evolution of craniotomy, we are going to base on these technical changes to organise in a more or less chronological way this development. It is obvious that these changes did not occur simultaneously or rapidly in all neurosurgical schools worldwide. They overlapped in time and it is not possible to describe them all. Therefore, we are going to make a historical tour and highlight the more important events with a long-lasting influence and which led to great developments and changes in the technique of craniotomy, as well as in the instruments required to carry it out.

It is an established fact that the adoption of craniotomy as a cranial opening technique instead of trepanning with a trephine crows was soon accepted in Europe, then in the United States and finally worldwide. The advantages were evident and the arguments supporting it were convincing. As a result, there was a shift in the technique thanks to categorical statements such as those affirmed in 1903 by George Marion (1869–1960), who pointed out that *'Des deux méthodes: trépanation, craniectomie, la dernière est à tous points de vue supérieure; elle seule permet de créer rapidement un orifice suffisamment large pour permettre une exploration complète du cerveau et une appréciation exacte des lésions. C'est la méthode de choix, qui tend à se substituer peu à peu à la première'* (Of the two methods: trepanation, craniectomy, the last is in every respect superior; it alone makes it possible to quickly create an opening large enough to allow a complete exploration of the brain and an exact evaluation of the lesions. This is the method of choice, which tends to replace slowly the first) [1].

25.1 Wagner's Temporary Cranial Resection

The origin of modern craniotomy can be established in Wilhelm Wagner's (1848–1900) description of the first temporary cranial resection to treat intracranial pathology in 1889 [2]. The term 'temporary' (*'temporäre'*) refers to the short-term nature, provisional or temporal nature of the cranial resection. Although the word 'temporary' might resemble the term 'temporal', we must not mistake the former with any anatomic element or any cranial or scalp anatomic region related to the latter (temporal muscle, temporal fossa or temporal bone). This type of cranial opening could be defined nowadays as an osteoplastic craniotomy with pedicle bone flap.

Wagner was fairly considered as *'the forgotten pioneer'* by M. Buchfelder and B. Ljunggren in a

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paper published in 1988 where they tried to claim the recognition of his work [3, 4]. These authors proved that Wagner had a great social, medical and scientific recognition in that moment, but it has been vanishing over time. One of the reasons why he was forgotten might be the administrative shift in Köningshütte, the town where he worked for many years until he died. This town, that belonged to the Upper Silesia and which was controlled by the Prussians and Germans, started being governed by Polish authorities after 1922 and was eventually incorporated to the city of Chorzów.

Wagner was a German physician who self-trained in surgery and became particularly interested in cranial and spinal surgery due to traumas. He was appointed professor thanks to his professional merits. He studied Medicine in Giessen and Marburg until 1869. Then he worked as a general physician as well as during the Franco-Prussian War. He was never trained in surgery so he self-taught by performing increasingly complex surgical procedures and studying and working with corpses. He got a job as a surgeon in the hospital of Köningshütte, a mining town in the Province of Silesia. There he became particularly interested in traumatic injuries, including cranial and spine traumas. He spoke and wrote about his experience with spine and spinal cord traumas based on more than 500 observations. In his book *'Die Verletzungen del Wirbelsäule und des Rückenmarks'*, which was published in 1898, he pointed out that he carried out the autopsy on all his deceased patients. His interest in traumatic injuries caused by work-related accidents also led him to hospital management.

However, his most representative work focused on describing the first osteoplastic craniotomy where the cranial fragment remains adhered to the deep side of the temporal muscle and scalp soft tissues, so that it can be replaced later back to its original position. Wagner thought that trepanation was a 'mutilating surgery' because it involved the resection of a portion of the intact bone of the skull. The purpose of the temporary craniotomy was to avoid resecting healthy cranial bone, which was necessary for the cranial opening with trepanation (as it was done by then). Hence, the brain was deprived from its mechanical protection. Although the scar, once it was formed, granted a covering (to a certain extent) for the brain, it is true that most patients required any type of helmet or external protection after cranial surgery. For this reason, he studied on corpses how to lift a flap from a certain area of the skull, with an appropriate size and which could remain linked to the soft tissues so that it could be replaced back to its position at the end of the procedure without suffering nutrient deprivation that prevented adequate cicatrisation.

Wagner published the results of these studies in the journal *Centralblatt für Chirurgie* on the 23rd of November of 1889 [2]. The article was titled *'Die temporäre Resektion des Schädeldaches an Stelle der Trepanation'*, which could be translated as *'Temporary resection of the cranial vault instead of trepanation'*. He described in his work the first comprehensive cranial approach as an alternative option to the trepanation carried out by then. The surgical technique followed these steps: large skin incision with the shape of the Greek letter omega (Ω) until reaching the periosteum; retraction of the margins of the wound, making a cut on the periosteum with a size of 0.5–1 cm parallel to the first incision; making a groove on the bone with the chisel and the mallet at 1–1.5 cm from the margins of the skin incision, deepening the bone groove and giving it a bevel shape on the curved area of the omega incision until reaching the dura mater; the osseous edges of the base of the bone flap were subcutaneously joined from both sides cutting the bone with a small chisel; and finally, the bone flap is lifted en bloc from the curved area along with all the superficial soft tissues to which it is adhered, including periosteum, temporal muscle with its aponeurosis, galea aponeurotica and skin. Once the intracranial procedure is over, the osseous-muscle-cutaneous flap was replaced. The bone adapts to the osseous receptor bed thanks to the bevelled cut. Finally, the soft tissues are sutured en bloc. The author highlights that the procedure is pretty easy in large approaches but it can be complicated in small approaches. He does not give much importance to the harmful effects of the intense hammering required for opening the skull on the patient's brain.

Wagner carried out previous experiences on corpses before applying his technique in a first surgery. In fact, it was done on a patient to evacuate a post-traumatic epidural haematoma. This intervention was carried out on the 1st of October of 1889. The patient, aged 27, had a cranial fracture and showed signs of endocranial hypertension. He was operated 2 days after his trauma but finally died 24 h after the surgery. During the patient's autopsy, Wagner confirmed the lack of haematoma and the usefulness of the approach to solve the problem, as well as the good nutrient supply of the osseous musculocutaneous flap that was achieved by an omega-shaped incision. He pointed out in his paper that this craniotomy would be useful not only to evacuate epidural haematomas due to the rupture of the middle meningeal artery, but also to remove brain tumours and abscesses, as well as to carry out cortical resections in epilepsy. Finally, he affirmed that his osteoplastic method was a cranial opening technique which was not more dangerous or difficult than an exploratory laparotomy. Wagner published in 1895 the results of the technique in other two cases of epidural haematoma that were successfully treated. One was due to the rupture of the middle meningeal artery and the other due to the rupture of the transverse dural sinus. When Wagner developed the osteoplastic craniotomy, he had the idea to solve many problems. Among them one was to obtain a large access to the intracranial space, but also to give the brain some protection as it would be deprived from its natural osseous protection if a definitive osseous resection was carried out. He also aimed to avoid a mutilating intervention by resecting healthy bone tissue. By keeping the bone flap adhered to the temporal muscle he aimed to guarantee the nutrient supply of the bone to avoid cicatrisation issues during the post-operative period.

However, as it happens many times, although the surgical technique was pioneering these solution proposals were not completely innovative. Some years before Wagner, in 1886, the French surgeon and anatomist Victor Chalot (1850–1903) established in his book *'Nouveaux éléments de chirurgie opératoire'* the usefulness of any osteoplastic method to replace the cranial bone if it was healthy by keeping it adhered to the soft tissues so that it could be reapplied after surgery [5]. In any case, an opening would be left to let the exudates of the wound come out. He suggested a trapezoidal incision with bone cutting until reaching the vitreous or inner lamina with the chisel on its three sides and the start of the base edge. Then he proposed placing a lifter beneath the vitreous lamina, between it and the dura mater, to fracture the rest of the inner lamina of the bone along the bone incision and the whole thickness of the bone in the basal pedicle. This intervention was only carried out in anatomic demonstrations. In a re-edition of the book in 1900 [6], which was entitled *'Traité élémentaire de chirurgie et médicine opératoires'* the author gathers the techniques created by Wagner, Chipault, Doyen and other authors along with his own methods. The author defends his own technique and states that it was similar to Wagner's, whose only merit has been to carry it out in patients. He then claims that *'Il serait donne juste, il nous semble, de rappeler opération de Chalot-Wagner'*. Wagner himself had already published in 1881 a statement describing the temporary lift of large flaps in two children with chronic sequelae and epilepsy secondary to cranial traumas.

Wagner's temporary cranial resection had an immediate success. Although this comprehensive approach by temporary osteoplastic craniotomy was designed for the treatment of complications derived from cranial traumas, its use was soon spread to other indications. Improvements of this surgical technique were proposed very soon, as the initial technical proposal thereof was indeed very crude. Wagner always defended bone resection with the chisel and the mallet and stated that he had never observed any negative effect that could be caused by the blows of the mallet (*'Verhämmerung'*), although he carefully examined his patients in search for them. We review below the attempts to improve the initial technique that we have described before.

25.2 Initial Development of the Wagner's Temporary Cranial Opening Technique

In spite of understandable initial doubts and resistances, classical trepanation was quickly dismissed in Europe and surgeons leaned towards temporary craniotomy. The technique thereof was soon improved when the use of the chisel and the mallet was discarded. The cranial opening made by joining several burr holes with the flexible twisted Gigli saw, which was introduced for this purpose in 1897, was systematised worldwide a few years after and became the success technique of cranial opening along decades. Before that moment and throughout ten brief years after the temporary cranial resection was presented in 1889 there were many technical developments to improve and facilitate the procedure, but most of them were ephemeral or unsuccessful. Other modifications were more long-lasting.

We discuss below the numerous modifications of Wagner's basic technique into manual opening techniques and opening techniques with electric motors. We are also going to describe both types and discuss the works of their supporters.

Some initial modifications of the temporary craniotomy with manual opening were included in the books *'Topographie cranio-encéphalique. Trépanation'* by Paul Poirier in [7], *'La trépanation du crâne'* by Leon Gallez (1864–1918) and published in 1893, *'Chirurgie opératoire du système nerveux'* by Antoine Chipault (1866–1920) and published in 1894 and *'Traité élémentaire de chirurgie et de médicine opératoires'* by Victor Chalot (1850–1903), which was published in 1900.

Hence, Poirier states that the surgical technique described by Wagner is a bit complex and that it can be simplified. Poirier suggests a list of modifications, for example, that the omega-shaped (Ω) incision is turned into a horseshoe-shaped incision by subtracting the horizontal lines of the base and with a pedicle of 3–4 cm or that all soft tissues must be incised in a whole. Müller suggests an intriguing modification by cutting only the outer table of the skull. Bruns suggested another modification in which he made a hole with a small trephine crown in every angle of the bone flap. This, according to the author, has the advantage of allowing to leave epidural drainages once the intervention is over. Chipault's proposal is similar, with two holes in the upper angles made with trephine crowns and two other holes placed in each end of the base of the flap, which were made with smaller instruments. Holes were connected by means of a special chisel that was 'protected' thanks to its H-shaped end to avoid damaging the dura mater. Others modify the designs of the chisel and the mallet to protect the dura mater or even the fingers of the surgeon.

The most interesting proposal concerning manual temporary craniotomy was made by the French author Jean Toison from Lille in 1891. This author expounded an osteoplastic craniotomy with a polygonal shape, either square, trapezoidal or rectangular, that was made by means of a chainsaw. To do so, he suggested making in each of the four angles of the flap some *'petites voies pour introduire la scie entre le crâne et la dure-mère, et scier celui-là de l'intérieur vers l'extérieur'*. These passages were actually small holes that were made with the chisel and the mallet until reaching the dura mater. Once the holes were made, a chainsaw had to be passed from one hole to the following one beneath the internal table and over the dura mater, which must be separated with a grooved probe. The bone was cut on three sides with the saw. Finally, the base was fractured by levering it with a chisel. Toison established that *'A ce moment, le premier acte de la trépanation* (craniotomy)*, c'est-á-dire l'ouverture du crâne, est terminé ... Le second acte, c'est-á-dire l'opération intracrânienne, terminé à son tour, on rapplique le lambeau ostéoplastique'*. Indeed, once the intracranial stage was over, the osseous flap was replaced and, according to Toison, there was nothing easier for the surgeon than making an osseous suture. It was carried out by making facing oblique drills on the edges of the bone. They must not end inside the skull and will be tied by means of a catgut or silver wire suture.

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26 Surgeons Between the Old Trepanation and the New Craniotomy

During the second half of the nineteenth century, before Wagner's temporary craniotomy, the approach of the intracranial space was still done by making holes with trephine crowns. Basically, they followed the procedure described in the Hippocratic texts, which had only suffered very few modifications and technical improvements throughout centuries and that has already been discussed in detail in the previous chapters. Actually, this limited cranial opening was normally enough in that time, as it was carried out to locate and evacuate post-traumatic blood collections or infections. The idea of enlarging the limited access provided by the trepan or the trephine was considered only in a few occasions.

Cranial surgeons started thinking about large cranial openings to meet these requirements. Victor Chalot (1850–1903) confirmed he was concerned about this issue when he pointed out that *'Un certain nombre de chirurgiens, Hoser, C. Hueter, Poirier, entre autres, sont portés, comme nous le sommes nous-mêmes, depuis longtemps, à remplacer la trépanation classique du crâne par la résection au ciseau et à la pince-gouge: l'appareil instrumental est ainsi réduit à la plus grande simplicité, et le manuel opératoire présente au moins autant, sinon plus de sécurité que celui de la trépanation'* (A number of surgeons, Hoser, C. Hueter, Poirier, among others, have been persuaded, as we have been for a long time, to replace the classical trepanation of the skull by resection by chisel and gouge-pliers: the amount of instrumental is thus reduced to the greatest simplicity, and the operative steps presents at least as much, if not more, security than that of the trepanation) [1, 2].

When reviewing the medical texts, it is possible to prove that the *'state of the art'* to enlarge the access provided by the burr or crown holes in the second half of the nineteenth century had not changed at all when compared to the technique used in the eighteenth century. A good example of this is the description of the surgical technique of trepanation made by Jean Marc Bourgery (1797–1849) in his *'Traité complet de l'anatomie de l'homme'*, which was published between 1866 and 1871. The print number 53 refers to the *'Trépanation des os du crâne et instruments du trépan'* with a still cross-shaped skin incision and *'de manière à pratiquer une large ouverture'*, by means of several grouped trepanations made by a trephine crown and homogenising the edges with bone-cutting forceps or the lenticular knife [3]. This technique is the same as the one that can be found in the English translation of the book *'Chirurgie'* by Lorenz Heister (1683–1758), which was published in 1745, more than a hundred years before and which reads as follows: *'When a Splinter is insinuated betwixt the Dura Mater and the Cranium, so that you cannot extract it by the first Aperture you made with the Trepan, a second or third Perforation must be made by the same Instrument, till you have removed everything injurious to the Brain and its*

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Meninges. Sometimes it will be necessary to cut off or remove the bony Fragments, by making a second Perforation into the first, like a half Moon, by the Trepan, when the Fragments are strong, or by the small Saw, by a Pair of cutting Forceps, or lastly, by the Mallet and Chisel …' [4].

At the end of the nineteenth century, the next generation of surgeons had the chance to know and put into practice Wagner's new temporary craniotomy. In general terms, the technique was quickly assimilated although there were some resistances. This was similar to what happened with the authors of the sixteenth century such as Andrés Alcázar and Giovanni Andrea della Croce. These authors knew and used ancient trepanning instruments in their youth, such as those mounted on a straight handle. However, when they published their works during their senescence both have already known and used the new trepanning instruments such as those mounted on T-handles or brace handles.

An example of this 'bridge' generation was the French surgeon Antoine Chipault (1866–1920). Chipault was considered the father of French neurosurgery. His life was dark and private and retired at a very young age. He published *'Chirurgie opératoire du système nerveux'* and *'Études de chirurgie médullaire'* in 1894 and *'Chirurgie nerveuse d'urgence'* in 1904 [5, 6]. Chipault gathered in detail the countless methods of cranial topography used in that time to localise brain cortical structures and also described the history of the cranial drilling techniques. He described his own cranial opening methods and also analysed systematically the 'cranial resection' techniques of that time, both old fashion and modern techniques.

He stated that in cranial resection the intervention starts by making a first hole, either with the trepan (which allows an opening of just a few millimetres) or with the trephine (which allows to make a hole with a diameter up to 50 mm). However, Chipault does not recommend these large holes due to risk of dural damage. The initial hole can be enlarged progressively by bone-cutting forceps, a saw or additional drills. The saw, which cut from outside-inward, could be a Hey's hand saw or a circular saw, which would be mechanically moved by a crank handle with a transmission belt. Additional burr or trephine holes were made to enlarge the opening after the initial hole. Chipault recommends the Farabeuf forceps, which were specially designed for this purpose as they had a solid support point on the edge of the skull. Another way of enlarging the cranial resection was by making one or more burr or trephine holes far from the first hole. In this case, the bone resection was completed by breaking the spaces of bone between the drills with the chisel and the mallet.

Chipault briefly described the express cranial resection with a chisel and a mallet, although he referred the reader to the chapter on Wagner's temporary cranial resection, which he described in detail along with some personal remarks and modifications added by other authors that we will later discuss. All instruments needed for cranial resection, regardless of their type, are shown by Chipault in the drawings of the book and were systematically included in the surgical instruments' catalogues of that time.

We can find an example of a more classical point of view supporting the trepanation during that critical moment for trepanations in Leon Gallez's (1864–1918) observations. He described the general technique in his book *'La trépanation du crâne'* in 1893 [7]. He accepts the crescent-shaped incision with a lower base but he explains in detail T or V incisions. He wonders whether it is possible to trepan in any part of the skull and admits that it can be done in urgent cases. However, it is wise to follow the recommendations made by ancient physicians and avoid trepanning on sutures or along venous sinuses. He wonder which is the best instrument to open the skull: *'le trépan, la tréphine, ou la gouge?'* and after discussing this issue he states: *'En résumé, jusqu'aujourd'hui, c'est encore le trépan à arbre* (trephine crown mounted on a brace handle) *qui compte le plus de partisans; je vais en décrire la manœuvre ainsi que celle de la tréphine* (trephine crown mounted on a T handle), *pour passer ensuite à l'exposé de la technique de l'opération au moyen de la gouge* (chisel and mallet) *et terminer par l'indication du procédé d'ouverture du crâne dû à Wagner, et qui mérite une mention spé-*

ciale'. (In summary, until today, it is still the tree trephine which has the most supporters; I will describe the use as well as that of the trephine, to then proceed to the presentation of the technique of the operation by means of the gouge and finish with the indication of the procedure of opening the skull due to Wagner, and which deserves a special mention.) When this author describes the trepanning technique, it looks like we could be reading the one described by the authors from the seventeenth or eighteenth century that were reviewed in the previous chapter. According to Gallez, the only advantage of Wagner's craniotomy is that it allows a very large cranial opening.

F. Terrier and M. Péraire show a more eclectic point of view, but still keeping this conservative mindset, in their book *'L'opération du trépan'*, which was published in [8]. They care about the areas to be trepanned, incisions and different shapes of the trepanation and express their preference about the chisel and the mallet due to their versatility and as the tapping on the patient's brain causes no impact.

Victor Chalot (1850–1903) published his book *'Nouveaux éléments de chirurgie opératoire'* in 1886 and described how to create large cranial openings: *'L'agrandissement de la brèche se fait par l'application de plusieurs couronnes juxtaposées ou empiétant les unes sur les autres et par la section des ponts ou promontoires intermédiaires a moyen de petites scies (scie de Hey, scie en crête de coq) ou des pinces-gouges'* (The enlargement of the opening is effected by the application of several crowns juxtaposed or encroaching on each other and by the section of bridges or intermediate points by means of small saws (Hey's saw, rooster's saw) or pliers-gouges). He used the same text in the re-edition made in 1900, although he already described Wagner's osteoplastic craniotomy. He described the trepanation and the typical points of trepanation based on the brain localisation doctrine in this same book. However, he states on a footnote that *'la détermination exacte de ces points a beaucoup perdu de son importance aujourd'hui, où l'on préfère les larges brèches crâniennes, soit définitives, soit surtout temporaires'* (The exact determination of these points has lost much of its importance today, where we prefer the large cranial openings, either definitive or especially temporary) [1, 2].

In short, all these authors and many others worldwide who worked by the time Wagner's temporary craniotomy was incorporated described the ancient techniques and the modern one in their books and stand for or against each of them. In that historical moment, at the turn of the century, it was common that cranial surgery texts were organised following the same structure. They all included a first part that focused on prehistoric trepanation. After that, they detailed the study of brain localisations and cranioencephalic topography, which were very novel aspects by that time. Then they described the material required for the trepanation, presented in detail all the historic and current instruments and finally focused on the description of the surgical technique of ancient trepanation and the novel craniotomy. In the end, they set out the indications and contraindications of trepanation and craniotomy, which was preferably aimed at traumas and with little attention to other intracranial and brain pathological disorders. It is remarkable that some authors devoted long chapters to the closing techniques of the cranial defect using the bone of the patient or other types of material.

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27 Eugène Louis Doyen (1859–1916), an Innovative French Surgeon and Enthusiastic on the Craniotomy

As an example of advancements and use of technical improvements and innovations regarding the primitive osteoplastic craniotomy we must highlight the impressive work carried out by the French surgeon Eugène Louis Doyen (1859–1916), who was an enthusiastic supporter and innovator of craniotomy.

Doyen was a very controversial surgeon due to his surgical speed and aggressiveness, as well as his turbulent private life. Concerning the medical and surgical field, Doyen developed the first modern surgical table. He also invented and used in surgery new conventional and electric instruments, also aimed at coagulation or radiology. His private and public life was very turbulent. He was a Freemason. He marketed champagne brand under his name as he was from Reims. He established a network of up to 20 private clinics in Paris, with particularly high fees. He also entered politics. His controversial professional life made him appear often in the newspapers. He also carried out daring clinical experiments, such as implanting tumour tissue on the contralateral breast after removing breast carcinomas in order to obtain immunity. His surgical separation of two Indian conjoined twins who were joined by the chest was also controversial. In his obituary the reporter says in the British Journal of Medicine: 'It is pity that one so gifted should have condescended to such devices in search of a notoriety which was quite unnecessary for his success' [1].

Doyen published the '*Traité de Thérapeutique Chirurgicale et de Technique Opératoire*' in 1909 [2]. The second volume thereof focuses on *'Operations sur la tête'* and describes in detail the technique of 'cranial opening or craniectomy', which was carried out with either conventional or electric instruments. The book includes many photographs of operations, in which, just out of curiosity, the author points out that although in the pictures the surgeons were not wearing rubber gloves, they frequently used them in surgical practice by the time the book was published.

Doyen described in his book the '*Craniectomie temporaire*', which he accurately defined as 'the intervention pictured by Wagner, from Köningshütte, in 1889. It consisted in moving an osseous flap with a certain size. The osseous flap remained adhered to the deep side of the skin flap and it was replaced back to its original position when suturing the surgical wound'. The author strongly supported the technique and admitted that *'la réalisation de la craniectomie temporaire par Vagner a été pour la chirurgie de l'encéphale un progrès considérable, puisque la nouvelle opération permettait de découvrir beaucoup plus largement l'encéphale, sans sacrifier*

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le volet osseux, que Vagner laissait adhèrent à un large pédicule cutané bien vascularisé'. He also pointed out that he ordered M.M. Collin to manufacture a new set of instruments in 1895 to substitute the crown trepans that had been used until then and promote the technique of craniotomy. He finally affirmed that *'l'oberture du crâne peut se faire in quelques minutes et le vollet osseux mobilisé peut atteindre une surface de 100 à 150 centimètres carrés, c'est-à-dire une dimension suffisante pour permettre l'exploration de toute un hémisphère cérébral'*. In this way, Doyen described the *'hémi-craniectomie temporaire'* in 1897. It was the largest and most sophisticated technique in technical terms of that time.

As we can see, Doyen was an enthusiastic supporter of craniotomy and he described two techniques in his works: one carried out with ordinary instruments, i.e. manual opening with a trepan and a saw, and another opening with electric instruments. We will now describe the former, as the one with electric instruments will be analysed later.

27.1 Ordinary or Manual Craniotomy by Doyen

Doyen divides manual craniotomies or those carried out with ordinary instruments into some stages: integument incision, mobilising the osseous flap, examination and intracranial procedures and finally closing and suturing the wound. He initially describes different types of incisions. They always had a horseshoe shape with a caudal base in order to have a centred access to the Rolandic fissure and the area of 'cortical motor centres'. He also described flaps for the frontal and occipital lobes and the cerebellum. Other incisions were aimed to remove the Gasserian ganglion. Doyen insisted on the haemostasis of the pericranial vessels with haemostatic forceps, ligation or transfixion points.

The manual cranial opening with conventional instruments described by Doyen had three stages: making several perforations on the skull with a drill, connecting the drills with a Hey's hand saw and finally fracturing the basal osseous pedicle. The head was shaved and washed the day before the intervention. It was covered with a dressing dampened with an antiseptic solution. An elastic compression bandage is placed above the ears as a preventive haemostatic measure. The middle line, along which the superior sagittal sinus runs, is marked. The incision is made with the scalpel until reaching the bone plane and the scalp edges are detached (Fig. 27.1).

The outer table of the bone is initially drilled with a flat trepan with a lancet tip mounted on a brace handle until reaching the diploe. The holes planned for the desired cranial resection are successively marked. The tip accessory is substituted by a grooved cylindrical or spherical burr and the surgeon continues trepanning until reaching the dura mater. Each pair of holes must be now connected with a saw, excepting for those in the base of the bone flap. To do so, the thickness of the skull is measured. This measurement is used to adapt a bone saw (which had been designed by himself) that has a regulating mechanism for the depth of the cut. In spite of that, he remarks that some spaces of bone between the holes are normally left uncut in the internal table. They can be cut with bone-cutting forceps or by tapping with the chisel. The base of the bone flap is cracked with the chisel and the mallet and then it is fractured by lifting the bone fragment by levering it with a periosteal elevator and making a backpressure with the fingers on the base of the flap. The bone cut is bevelled so that the bone can be later replaced easily without dipping inside the skull. The bone fragment is always joined to soft tissues forming a single flap that is dislocated and fixed with the assistant's fingers during the whole intervention. Once the intracranial procedure is completed, the bone flap is replaced back to its original position. Sometimes it is difficult to adapt the bone flap in the fracture line. Hence, it is possible to cut out any unevenness with the bone-cutting forceps that Chipault

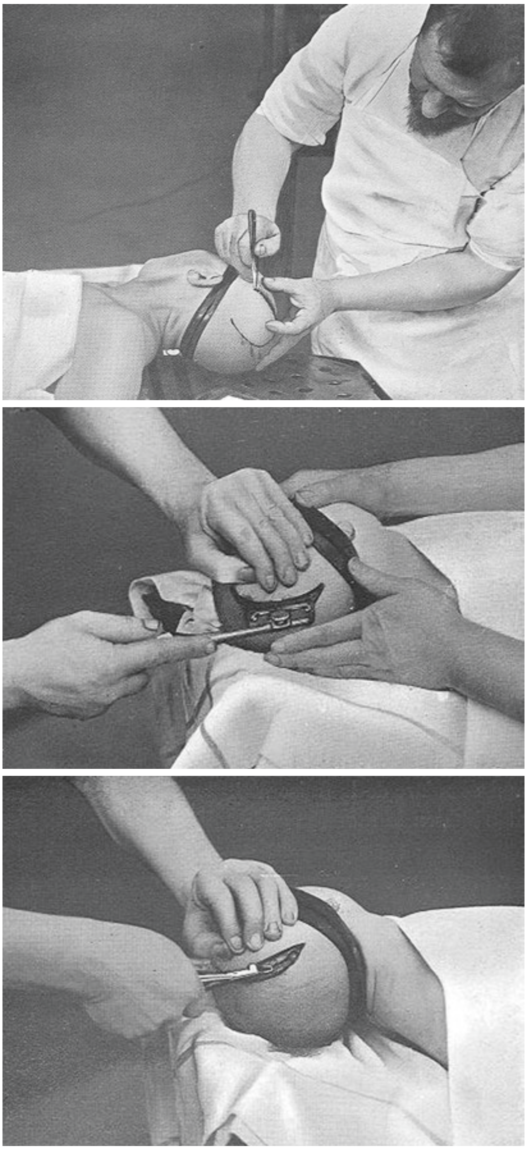

Fig. 27.1 Craniectomy with manual instruments. Upper: Shows the section of the soft tissues. An elastic rubber is applied around the head for preventive haemostasis. Centre: Shows the section of the outer table of the skull with a saw. Lower: Shows the section of the whole skull with a bone forceps (Doyen E. Traité de therapeutique chirurgicale et de technique opératoire. Paris: A. Maloine: 1909)

has designed for this purpose. The soft tissues are sutured in a single plane with curved needles. The suture can be either continuous or by separate stitches. Finally, a cap-shaped bandage was applied.

Doyen shows in a photograph the surgical material necessary for craniotomy, with either manual or ordinary and electrical instruments (Fig. 27.2). In the bottom row is the general opening instruments and in the centre and on the right the closing instruments. The instruments for manual or ordinary craniectomy are 1 trephine with a flat tip of 12 mm, attachment with conical drill of 12 mm, attachment with cylinder-spherical drill of 12 mm; 1 compressor for bleeding of the dural sinuses; 2 straight and curved elevators; 1 instrument to measure the thickness of the skull; 1 dura mater separator; 1 saw; 1 bone forceps for skull; 1 gouge claw; 2 craniotomy scissors; 1 hammer; and 2 cutting claws, right and left, for the irregularities of the bone flap. The electrical instrumentation includes 1 lateral tilt handle; 2 attachments with 12 mm spherical cutter; 1 attachment with 35 mm circular saw and protective disc; 1 set of discs graduated in millimetres; saw with alternating teeth, 45 mm; 1 saw holder with intracraniald guide; and 1 screwdriver.

27.2 Electric Craniotomy by Doyen

Doyen explains in detail the craniotomy with electric instruments in the chapter entitled *'Craniectomie temporaire'* of the second volume called *'Operations sur la tête'*, of his book *'Traité de Thérapeutique Chirurgicale et de Technique Opératoire'* from year 1909 (Figs. 27.3 and 27.4). He described in first place the ordinary or manual methods we have already mentioned but later rejected these manual systems as he considered them inefficient.

Concerning his electric instruments, Doyen developed a system with two motors with direct and alternating current. He stated that the burrs and the saw had to be powered by an electric motor of ½ horsepower spinning at a speed of 2500 rpm. He affirmed that he ordered to make a flexible shaft in 1895. It was so powerful and

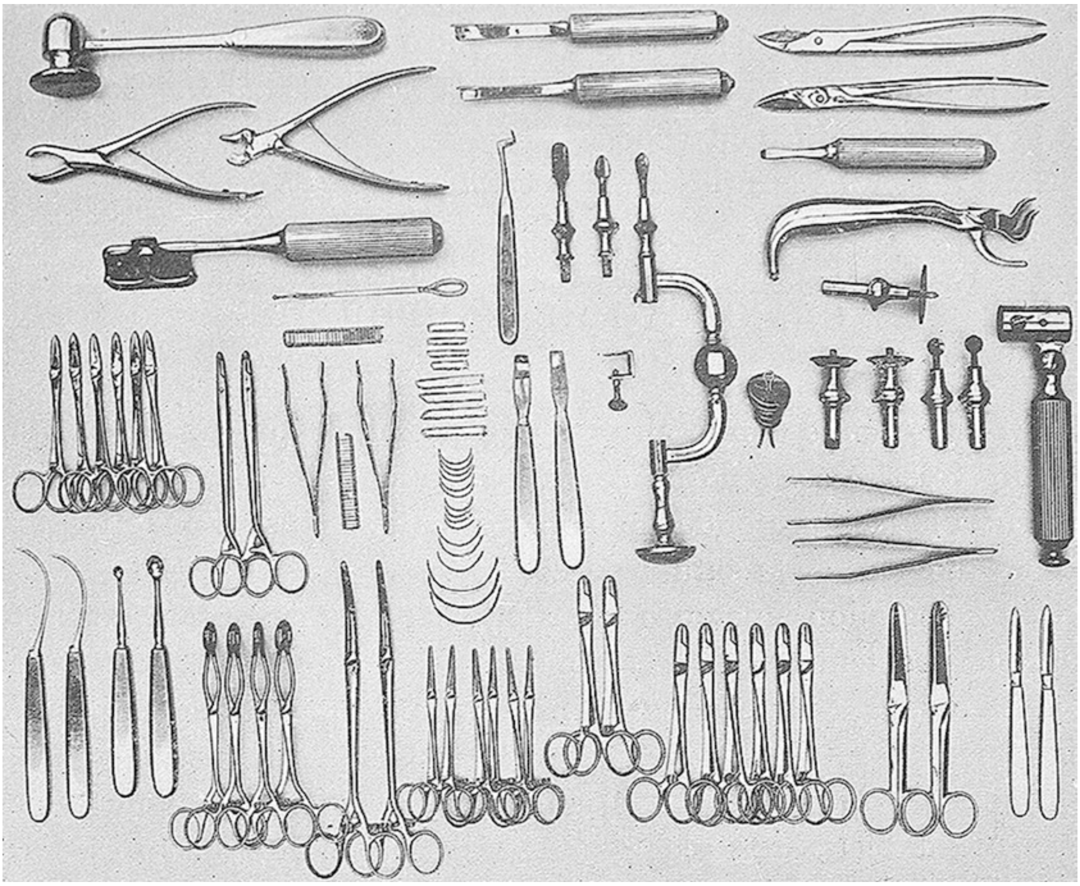

Fig. 27.2 Surgical material necessary for craniotomy, with either manual or ordinary and electrical instruments (Doyen E. Traité de therapeutique chirurgicale et de technique opératoire. Paris: A. Maloine: 1909)

safe that there was no risk that the transmission could unexpectedly break or that there could be a sudden shutdown. The hose with the flexible shaft was 1.5 m long and had a piece on one end that allowed a longitudinal (burr) or perpendicular (circular saw) cut when compared to the rotation axis. Accessories could be adapted to this end. He pointed out that the available ½ horsepower motors with direct current allowed a speed of 2000–2500 rpm and those with alternating current only spun at 1100 rpm. Hence, the latter required a mechanical system to double their speed. The second problem of alternating current motors was that they had to be started before the intervention and could not be stopped until it had finished. For this reason, the motor that Doyen used had an automatic clutch braking system in order to stop the burr or the saw. This way, when the surgeon ordered so (*'Halte!'*), the electrician assistant operated a lever that moved the motor belt from the transmission pulley to another pulley with an idler pin. The shaft onto which the hose was mounted had to be placed at a height of 1.50 m. There were many drilling and cutting accessories that could be adapted to the distal end: spherical burr of 12 mm; circular saws with alternating teeth of 45 mm; and finally two thin circular saws of 35 mm with some discs n.4 and n.5 that restricted the cutting depth in the bone to 4 mm and 5 mm, respectively.

He used the burr with a diameter of 12 mm to make the initial holes. It was placed at an angle of 30° over the skull and after giving the command *'Allez!'* the electrician assistant operated the lever thereof. The burr was placed in an increasingly vertical position and it was pushed against the bone until its midpoint started penetrating the outer table. At that time, the whole thickness of the skull had already been drilled and there was a risk of violently invading the intracranial space. Therefore, it was removed. Making each hole took about 5–15 s, depending on the thickness of the skull. Two holes were made on the base of the flap and one or two more were made along the cutting edge of the bone, which had been previously marked. The dura mater between the holes was then separated from the internal table by means of a flexible separator with the shape of a needle or a grooved probe with an enlarged end. He used the circular saw

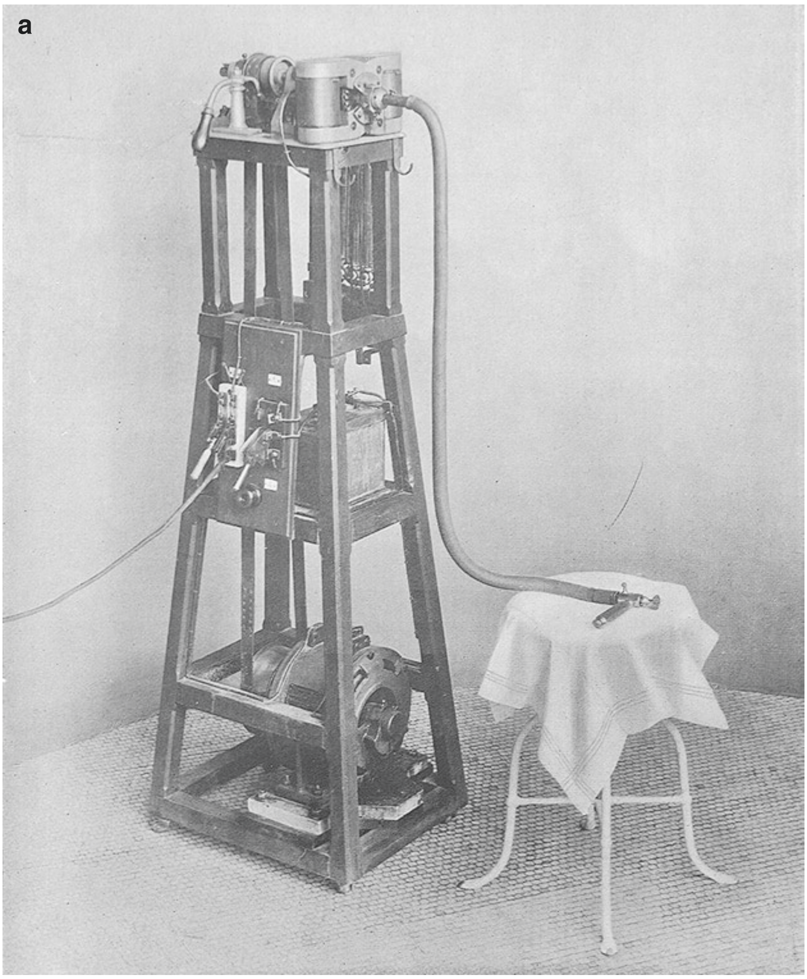

Fig. 27.3 Electric instruments. (**a**) The figure shows the support with the two electric motors, in the bottom the alternating current motor, connected with a transmission belt to a pulley that will command the flexible shaft. At the command of 'Halte!', a lever passes the belt of the drive pulley on a crank pulley. At the top right is the DC motor on which the flexible shaft is mounted with the variable tilt handle and a 35 mm saw. (**b** upper) Shows the use of the perforator. (**b** lower) Shows the use of the circular saw with dural protection for cutting the whole thickness of the skull. (**c** upper) Shows the cutting of the whole skull using a circular saw with a pre-selected deepness of cutting. (**c** lower) Osteoplastic craniotomy (Doyen E. Traité de therapeutique chirurgicale et de technique opératoire. Paris: A. Maloine: 1909)

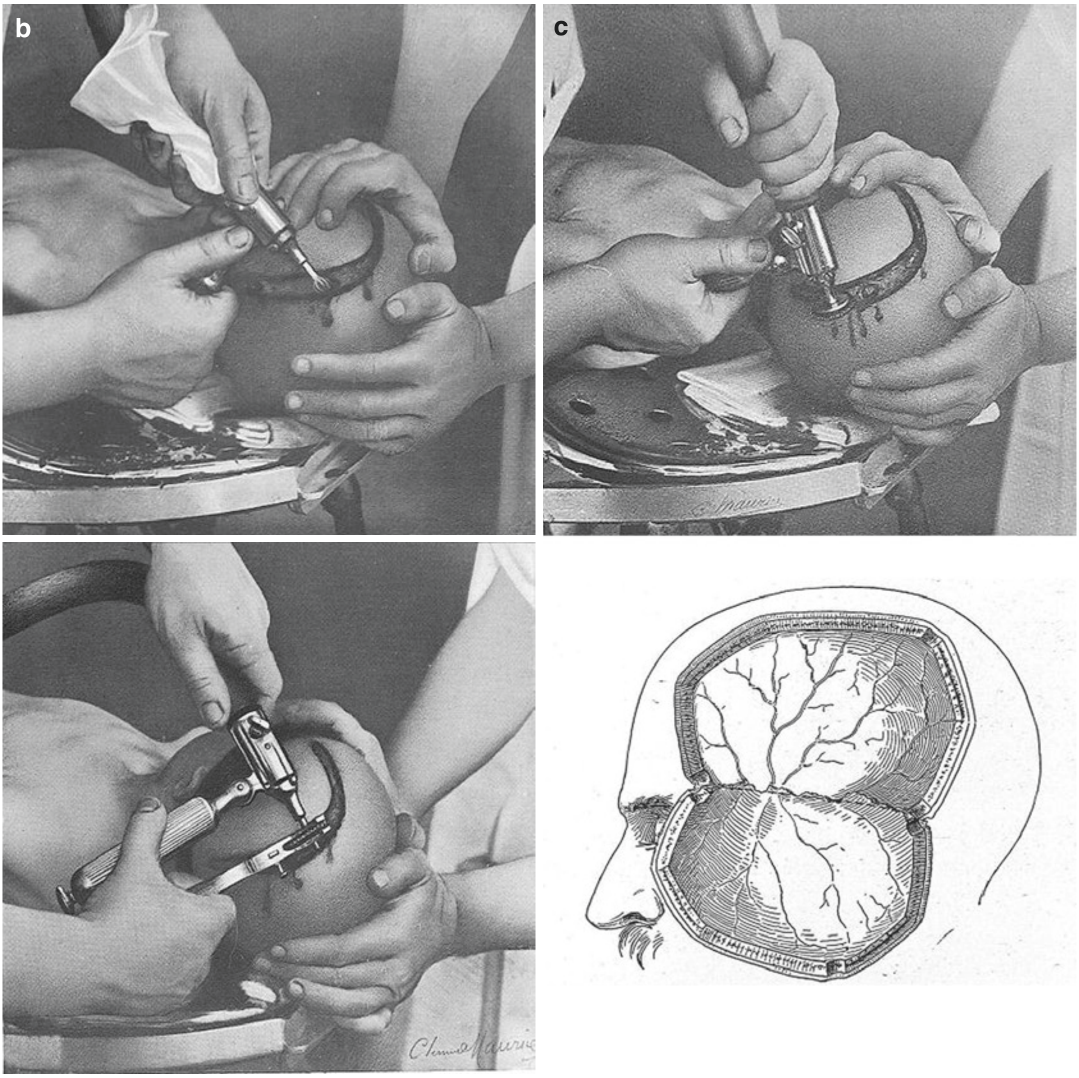

Fig. 27.3 (continued)

with a diameter of 45 mm coupled to a handle with an intracranial bolt (which prevented the dura mater from being cut with the saw) to connect the holes and cut the whole thickness of the bone. However, to prevent the bone flap from dipping inside the intracranial space Doyen suggested leaving some linking areas in the internal table of about 2–3 cm on each side of the cutting line. In order to do so, he used the thinnest saw (35 mm) which had some discs that restricted the cutting depth and adjusted it to 4 or 5 mm, depending on the thickness of the bone. These linking areas that had been left intact were broken at the end by tapping a chisel with a mallet. The chisel had some kind of wings which prevented it from dipping as they sat onto the surface of the outer table. The osseous flap was finally released by fracturing its base, which was in turn weakened by tapping the chisel. The bone flap was always connected to the soft tissues and was held by the assistant with his or her fingers throughout the whole surgery. The stages of preparation, the intracranial procedure, the closure and the wound cleaning were identical to those described in the manual technique with ordinary instruments.

Fig. 27.4 Several photographs of the craniotomy technique with electric motor. (**a** upper) Perforation of the skull with the 12 mm spherical bur. (**a** lower) Cutting with the saw of the entire thickness of the skull, with the intracranial guide for protecting the dura mater. (**b** upper) Cutting bone bridges with a circular saw. (**b** lower) Cutting internal table remnants with a protected chisel and hammer. (**c** upper) Intracranial exploration and dura mater opening. Note in what way the assistant holds the head of the patient and the flap. (**c** lower) Opening of the dura mater with the aid of a probe (Doyen E. Traité de therapeutique chirurgicale et de technique opératoire. Paris: A. Maloine: 1909)

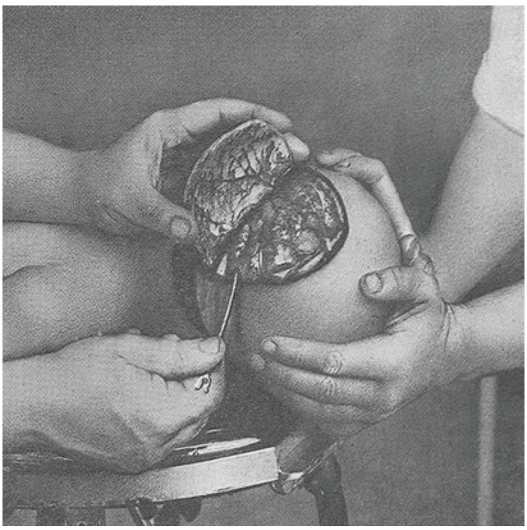

Fig. 27.4 (continued)

During the description of the technique, the author highlighted that it was necessary for the assistant to hold firmly the patient's head. This also had to be done by the surgeon when working with the cutting instruments, particularly the saw. We must remember that no cranial fixation system was used in that time. He repeatedly recommended to test the instruments in anatomical specimens and to study the surgical technique by watching his film on this issue.

27.3 Doyen's Pictures and Films

Doyen was an enthusiastic of the operative photography and film recording [3]. Dozens of surgeries were recorded and some of them are still stored in public and private film libraries and collections and available in the Web. Doyen gave his lectures showing images and films. Pictures of the operating rooms are particularly effective and dramatic (Fig. 27.5b). Baptista reviews the filmography by Doyen stored in the Cinemateca Portuguesa's collection in Lisbon referring some shots of craniotomy and intracranial procedures.

However, there are two spectacular photographs recording two surgeries by Doyen that deserve a particular interest. In 1914 Doyen publishes a scene where the surgery of a craniotomy in a young afflicted with Jacksonian epilepsy was photographed [4]. Surgery was carried out on August 7, 1900, in the presence of Prof Virchow, the famous German scholar and other surgeons who attended the International Congress of Medicine in Paris. The patient is anesthetised, with a nun acting in this role; the surgeon and assistants are dressed in street clothes, with an apron and uncovered arms; on the right side is placed Doyen's motor for the electric craniotomy; behind it is the amphitheatre where, in several rows, there are the assistants and guests, whose names are detailed in the foot of the figure. The intervention is done in an operating room, where light was provided probably by large windows and electrically powered light (Fig. 27.5a).

This picture is similar to other one, where a craniotomy is also carried out by Doyen at the International Congress of Medicine in Moscow, in 1897, in this case in the presence of other famous surgeons, such as Prof. von Bergman of Berlin, the second on the right, or Prof. Simpson of Edinburgh, in the centre (Fig. 27.6). The composition of both photographs, particularly the last one, is reminiscent of the paintings of the anatomy lessons of the Flemish painters of the seventeenth century. On the right, one of the surgeons present holds in

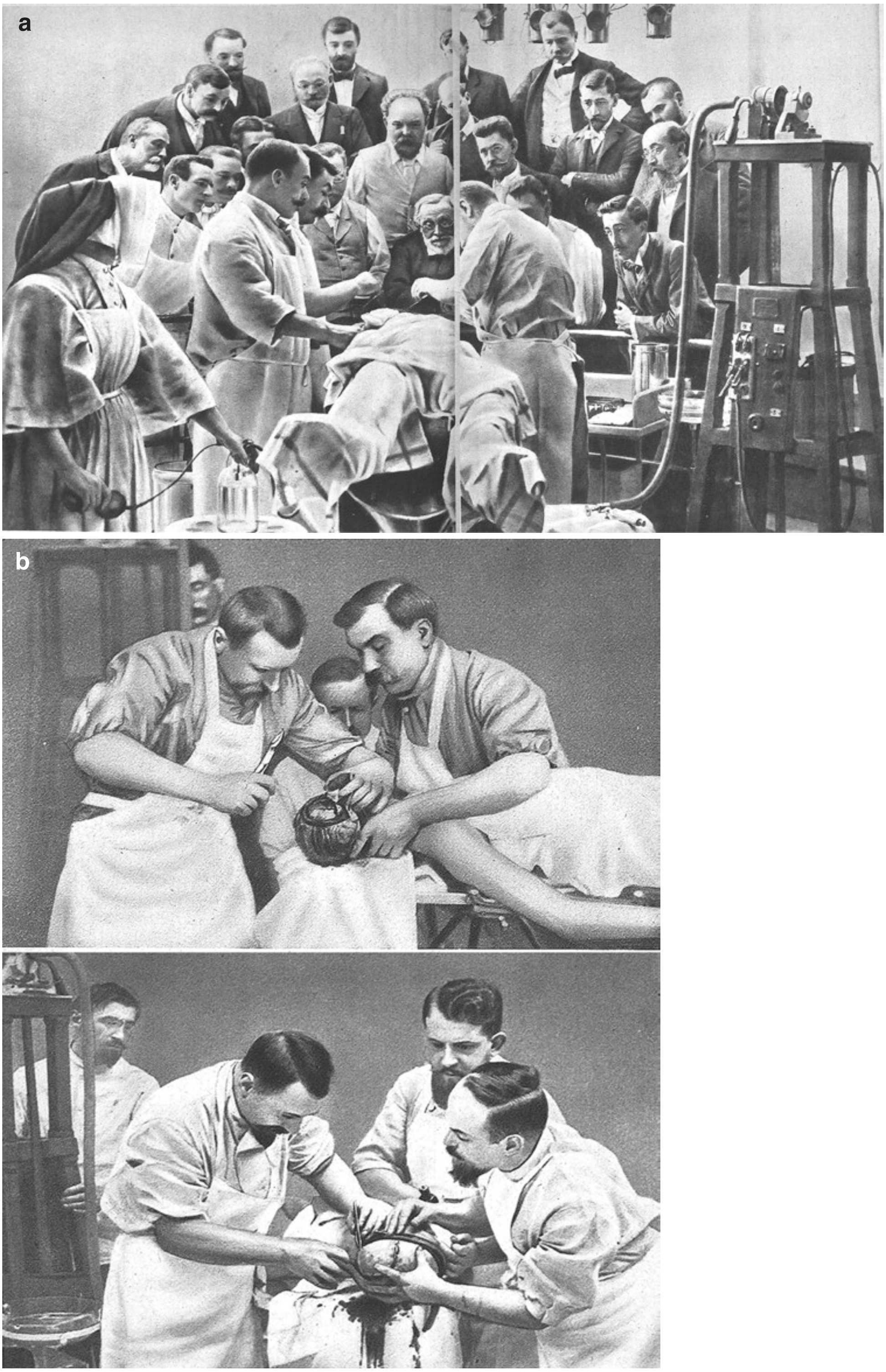

Fig. 27.5 Photographs of surgeries done by Eugène Louis Doyen. (**a**) Craniotomy for the treatment of a Jacksonian epilepsy photographed in 1914. (**b**) Two images taken from movies of craniotomies carried out by Doyen (Doyen E. L'émotion chez le chirurgien. Je sais tout. 1914; 110: 357–376)

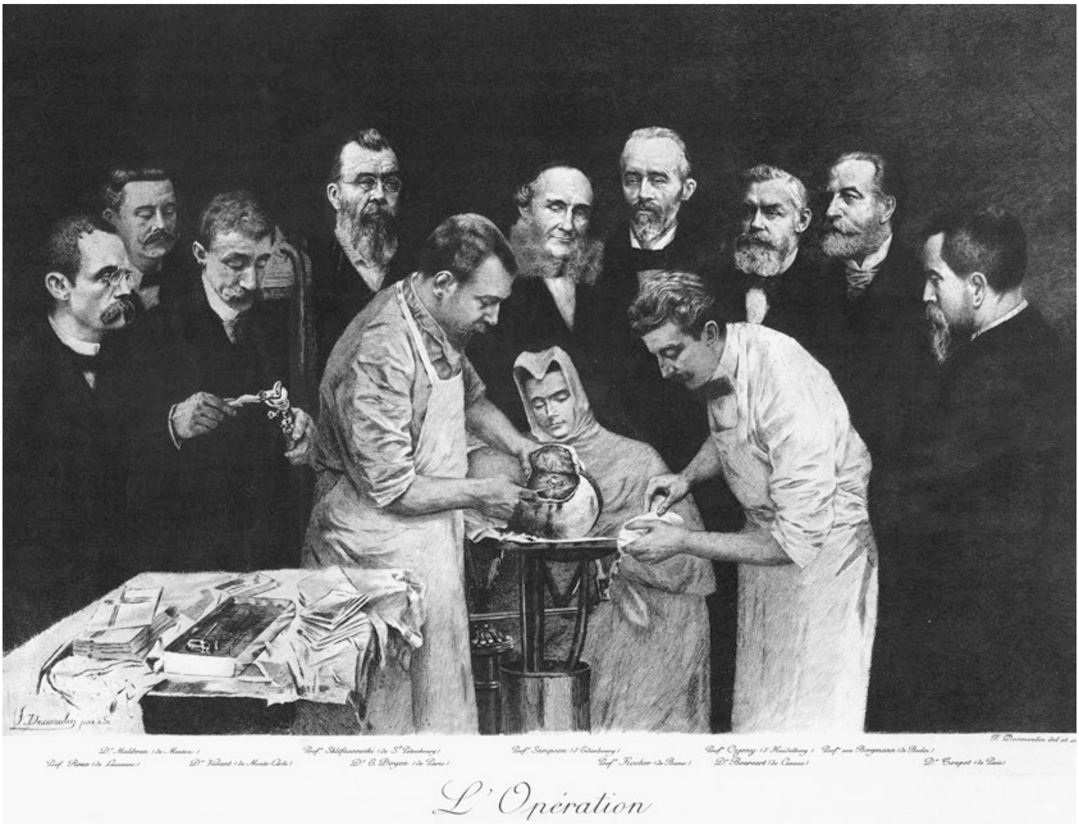

Fig. 27.6 Craniotomy carried out by Doyen in 1897 in the International Congress of Medicine in Moscow, in 1897

his hand and looks at Doyen's electric craniotome. The British Medical Journal described the participation of Doyen in the Congress as follows: 'Craniectomy for Microcephalus. M. Doyen (Paris), at the combined sitting of the Surgical and Neurological Sections, reported some remarkable results on the result of craniectomy in microcephalus. In one case, complicated with goitre, the goitre disappeared, and the intelligence so improved that de patient, aged 15, was successfully taught to speak' [5].

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28 Surgical Instruments for Craniotomy and the Success of the Humble Gigli's Saw

The same instruments that were used for trepanning were also employed for the first craniotomies. However, it was soon necessary to develop new tools that could be adapted to the new technique of craniotomy. The technical development of that time allowed to introduce modern manual and electric-powered mechanic systems soon among the instruments of choice. The proximity of the historical events and the great amount of documentation allow to have a good knowledge of the technological solutions that were implemented, as well as of their success or failure.

Although the first modern craniotomy was carried out with a chisel and a mallet, a new method of craniotomy was soon standardised. It consisted of making the osseous resection by drilling around its perimeter several small burr holes, which were subsequently connected by cutting the bone between them. This successful model ended up being worldwide accepted. We will now describe the instruments required for drilling and cutting (Fig. 28.1).

28.1 Instruments for Cranial Drilling

The manual drilling of small holes on the skull was already described in the Hippocratic texts and it was carried out by drill-like instruments called '*terebra*'. Cranial drillings of a bigger size started becoming more frequent during the Renaissance and later. They were carried out by trephine crowns, present in versions of the ancient '*modiolus*', with a diameter of up to 5 cm, and the small drills and punches were considered tools that were used to start the trepanation. Large holes (such as those achieved with the trephine) were not required to carry out a craniotomy. For this reason, the driller with a small diameter returned and played again an important role. Hence, the first step of an osteoplastic craniotomy consisted of making several drills of small diameter, usually less than 15 mm. The most suitable tips and handles were selected over time and the perforation method changed from the trephine crown to the drill.

Fine drillers with pyramidal or punch-like tips and T-handles were widely used at the end of the nineteenth century and at the beginning of the twentieth century. They were used to drill the infected bone with the aim of evacuating the underlying necrotic and purulent material. They were useful on the skull in those cases of pyogenic mastoiditis to drain the purulent material by making one or several separate drills. The bone is very thin in the mastoid process as the mastoid cells are located right under a fine layer of cortical bone. As the infected bone is softer, it makes it easy to drill with this type of simple sharp instruments, allowing to evacuate the pus. For this reason, the design of these drills remained identical to those ones used by ancient and medieval surgeons and were employed with the same

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Fig. 28.1 Photographs of the surgical instruments used for osteoplastic craniotomy used until the end of the last century. (**a**) Manual opening. Drilling instruments, with a brace handle of Hudson, with different accessories of perforation. There is a perforator in lancet, and four perforators with a grooved surface, one cylindrical, one conical and two spherical with a different diameter. (**b**) Bone-cutting instruments. Above is the double-braided saw of Gigli that ends in two rings where the holders of the handles are hooked. Below has been photographed the driver of the saw, metallic, flat and elastic, which ends in a widening and that has a hook a few centimetres away to thread the saw in its passage under the bone. (**c**) Electrical powered opening. Set of attachments for cutting the bone with a vertical saw is shown, above on the right. The central head allows the rotation but the left in fixed. On the right there is an electrical engine with a spherical burr and next to it several fine drills. Below there are six drills of different diameters, one of them mounted on the engine. All instruments are made of steel and reusable by sterilisation

purposes. However, these small perforators were never employed in craniotomies due to the risk of piercing the dura mater and damaging the brain.

Instead, other drilling tips were used for the craniotomy holes. The holes were initially made with a lancet-shaped driller and the bone was drilled until the dura mater was visible in the central area. To prevent the lancet from dipping it was substituted by a second solid drilling tip with a spherical or truncated cone shape and a grooved surface. This allowed to enlarge the hole of the internal table without eroding the dura mater or dipping in the brain. Surgeons used drillers of increasing sizes to obtain the expected diameter. Concerning the handle, the T-handle was discarded and substituted by a brace handle, which was more efficient in mechanical terms and also more comfortable for the surgeon. This was particularly obvious if the patient's head was firmly fixed to the operating table with the help of an assistant or by a cranial fixation system and also because for craniotomy always several holes were necessary. The handle normally had an extension to make it easier to drill in the posterior fossa. The drilling tips could always be easily interchangeable onto the handle.

Lastly, the successful instrument for making craniotomy holes was designed and patented by Robert J. Hudson in 1877. It was used by neurosurgeons worldwide until the end of the last century. The instrument has a brace handle as well as a set of several interchangeable drillers. We must point out that this modern instrument accurately reproduces some of the designs from the sixteenth to nineteenth centuries that we have described in the previous chapters, both concerning the handle and the drilling tips, but it does not include any revolutionary improvement. This instrument is no longer used and has been set aside in some catalogues or remains at the bottom of the surgical instrument containers since it was definitely replaced by the electric or air motors.

The first electric motors used for drilling the skull were introduced very early, at the beginning of the twentieth century. However, due to reasons that will be later explained, they were substituted by the manual drilling that has been used until the definitive reintroduction of modern motors. Air- and electric-powered motors were reintroduced in the 60s of the last centuries. Each type of motorisation has had different drilling instruments.

The first electric motors spun at a very low speed. Interchangeable drillers with the shape of grooved spheres could be mounted onto them. They allowed to cut the bone in all directions and with all inclinations but they had a short life. They had new designs that were more reliable, powerful and solid.

These new motors required the design of new perforators: bit-shaped drillers with a braking mechanical system which blocked the rotation of the drill when the internal table was pierced (Fig. 28.2). These drills, called now perforators, have a central boring bit and an outer crown that rotates freely. The crown stops the spin of the bit when the crown is blocked after pressing firmly against the bone of the outer table of the skull. This happens when the tip of the drill slightly dips into the skull after surpassing the resistance of the internal table. There are different models that have been designed and manufactured by different medical equipment companies. Those initially developed by Codman & Shurtleff Inc. were particularly famous. The first perforators with brake were used both in manual and motorised handles. However, in the end they were exclusively used for the latter. In order to effectively use this type of drillers the spinning speed of the motor must be around 800–1000 rpm (revolutions per minute). The hole is made by keeping the motor stable, exerting a constant pressure vertically until the spin automatically brakes. The diameter of the drill and the depth of the cut that is allowed can be variable and the surgeon uses the one they consider to be the most suitable for each specific case, particularly for paediatric patients. These drillers only allow to make circular holes and with a maximum predetermined diameter of no more than 14 mm, similar to the driller chosen. The drill produces bone sawdust and it usually leaves a very thin layer of bone from the internal table at the bottom after braking. This layer, which is not fixed to the dura mater, can be removed by levering it with a fine dissector. As a result, we obtain a cylindrical hole on the bone. These instruments were widely used to make the holes that were necessary for a craniotomy and, once in a while, to make burr holes for examination, to insert cannulas, catheters and electrodes or to evacuate a chronic subdural haematoma.

When the high-speed spinning motors that reached 100,000 rpm appeared later, these perforators with braking systems could not be used any longer. They must be used with motor reductors that reduces significantly the speed of the motor to 800–1000 rpm. However, high-speed motors allow making holes on the skull with very small drillers. Hence, it is possible to use grooved drilling accessories or burrs that are spherical or have the shape of a match and a diameter of a few millimetres. The accessory is gently applied onto the outer table, which is drilled due to its high spinning speed. The surgeon, by making circular movements, achieves perfect circular holes with the diameter he or she wants. The problem is that these drillers do not have a braking system and the dura mater can be eroded easily. This is why the surgeon must be very careful when reaching the internal table. When the dura mater has been exposed, the resection of the rest of the bone of the internal table is completed with a fine laminectomy punch (number 2). Another problem is that the high spinning speed generates a lot of heat and bone sawdust. For this reason, it is necessary to constantly wash and cool with cold saline solution.

All types of drillers were reusable at first but disposable models were soon manufactured. The single use guaranteed sterility, security, cutting quality and motor durability and avoided biological contamination between patients.

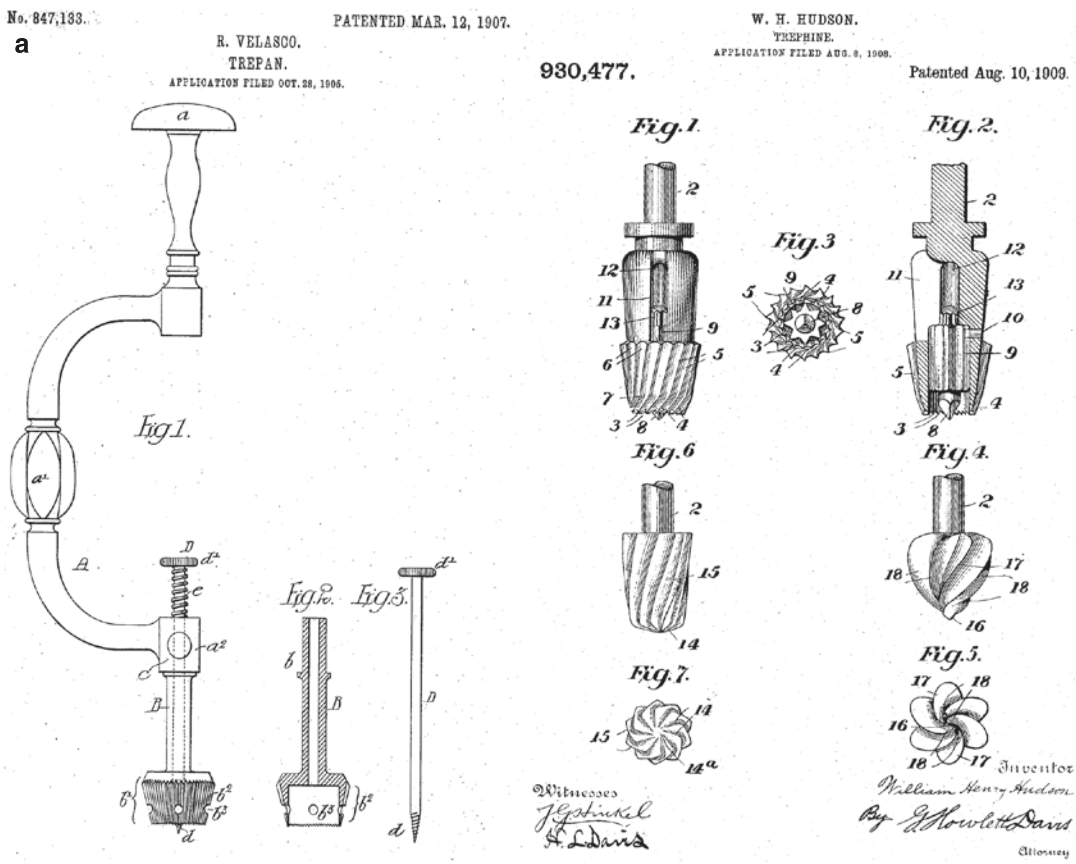

Fig. 28.2 Photographs taken from patents of the United States of different instruments for trepanation. (**a**) Trepan of Velasco (1905) and trephine of Hudson (1909). (**b**) Trepans with automatic braking patented in 1947 and 1984, and rotatory vertical saw from Codman (1978) (United States Patent and Trademark Office, https://www.uspto.gov)

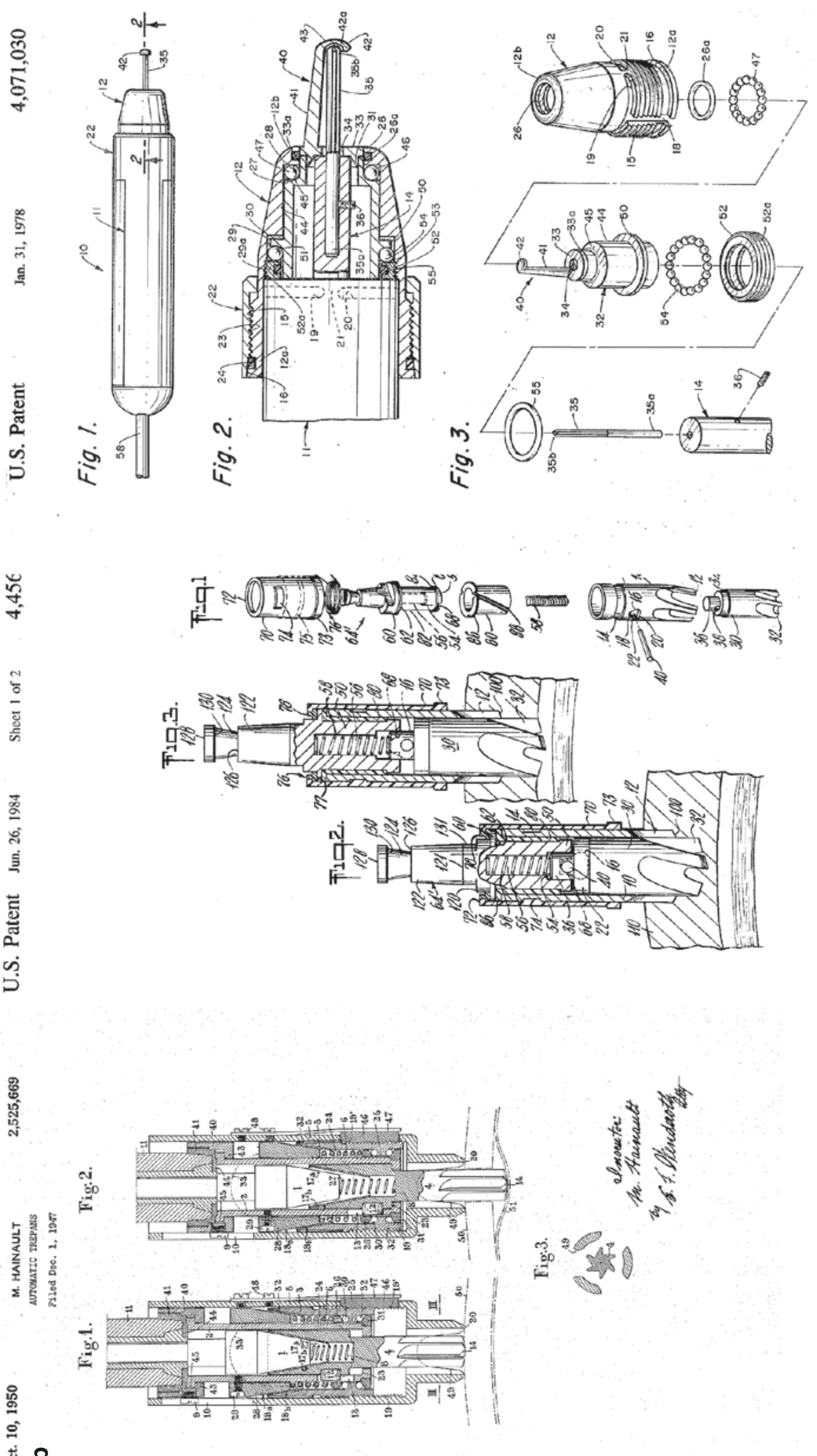

Fig. 28.2 (continued)

28.2 Instruments for Bone Cutting

We have seen that the usual way of enlarging the trepanation before craniotomy was invented always consisted of making several trephine holes that were grouped or connected with a chisel or a saw cut. In Wagner's original osteoplastic craniotomy, the bone was cut directly with the chisel and the mallet, without making holes. However, the most typical instrument to cut the bone between the burr holes in the craniotomy has always been the bone saw.

When the practice of craniotomy started there was a heated discussion about the type of saw concerning the cut of the bone: from outside-inward or from inside-outward. The former, which are illustrated by Hey's saw or circular saws, were considered dangerous as the dura mater and the brain were put at risk, regardless of having stops to control the depth of the cut, like in the Doyen's circular saw. The latter, represented by the chainsaws or Gigli's saw, were considered safer because once they were adequately used to make the cut, they could damage neither the dura mater nor the brain. On the contrary, the risk of harming the dura mater and brain lied in the moment when the saw passed under the bone.

Leaving apart these important considerations about the use of bone saws to cut the skull, we are going to describe the types of saw in terms of design: straight, circular, vertical-cutting saws, chainsaws and braided-wire saws.

The traditional method to cut the skull involved Hey's manual straight saws, which have already been described previously. They make cuts by means of a swinging motion which is difficult to control. If these straight saws are used with motors the fine control is worse. Straight saws cut the skull moving from outside-inward. This is why they were completely contraindicated for cutting the skull in the craniotomy. The alternative options were circular and vertical-cutting saws.

Circular saws cut the bone in a perpendicular plane to the axe of the saw. They were initially coupled with manual motors that were powered by a crank handle. They were connected to electric motors soon but did not become very popular as they cut from outside-inward, and the danger of dura mater or brain damage was high in spite of having dura mater protections from the beginning. The first modern reference concerning the use of motors in neurosurgery was by Sir Victor Alexander Haden Horsley (1857–1916), who used Bonwill's manual circular saw in 1887. He did not consider it useful and dismissed it soon. Nevertheless, circular saws were occasionally used. William Williams Keen (1837–1932) mentioned its use by Krause to carry out the craniotomy for a trigeminal rhizotomy. In this intervention the surgeon holds the saw shaft with both hands, as it can be seen in a vivid figure. Eugène Louis Doyen (1859–1916) designed a circular saw that was perpendicularly coupled to a rotation axis that was powered by an electric motor [1]. The saw was mounted on a handle that allows the surgeon to hold it firmly. The surgeon can also adapt the depth of the cut to the thickness of the skull and has a dura mater protection. As we have already mentioned, all of these circular saws did not have much significance in craniotomies and were soon rejected.

Vertical-cutting saws are currently the basis for cutting the skull. They became the successful design after being mounted on modern air or electric motors. Vertical saws did not have a dural protection at first. This is why there was a high risk of cutting the dura mater. After several attempts, M.H. Cryer invented a vertical-cutting spiral saw with dura mater protection that was mounted on an electric motor in 1893. Its design was very similar to modern equipment. However, the system was not successful by that time. The reason was because they used to think that the vibration caused by the motor was harmful to the brain. For these and other reasons vertical saws were forgotten during decades, more than 50 years.

At the end, modern electric or air motors were coupled to vertical-cutting saws in the second half of the twentieth century. This allowed cutting the bone easily and quickly. As they generated heat and bone sawdust it was necessary to constantly irrigate with cold saline fluid. The cutting instrument has a shank that is placed parallel to the saw. It has an angled end, where the saw can be held so that it does not become bent. The angled end, which is a bit thickened, protects the dura mater during the bone cutting. The last improvement of these saws includes an axis that rotates freely. This allows sawing off the flap with the shape intended by the surgeon. The first design of a rotating vertical saw was created by Codman & Shurtleff. The technical drawing of the mechanism was included in the patent registered in the United States. A first burr hole is necessary and also separation of the dura mater from the bone to start cutting with a vertical saw. If the bone cut ends in the same hole, an osseous flap can be lifted with just one burr hole. Other times two or more holes are made and the bone between them is cut. These saws cause more damages to the dura mater than desirable as the separation of the dura mater is not usually completed between the holes. Current high-speed motors are particularly useful to cut the bone with a vertical saw.

We must keep in mind that during the first stages of craniotomy (that is, at the end of the nineteenth century) the most efficient cutting saws were saws with cutting teeth in just one side or chainsaws. Chainsaws were used in surgery to cut long bones, especially in amputations. Sometimes, the purpose of cutting off the bone was to cut out the fractured segment of the long bone and place both ends facing each other to join them, avoiding thus amputation. Chainsaws consisted of long series of short pieces with a cutting edge on one side that were joined together by strong bolts. The saw was connected on both sides to elements or handles that were manually held so that they could be handled once they had passed under the bone. The chainsaw exerted some friction on the bone due to the swinging movement the surgeon made but he finally got to cut it. Manual cutting of bones with chainsaws was arduous and not very efficient from a mechanical point of view. Jean Toison recommended chainsaws in craniotomies in 1891. They were used to cut the bone between a pair of square holes that had been made with a chisel on the skull. The saw was conducted by the surgeon, who held two handles that were located in both ends, cutting thus the bone from inside-outward. Some years before, in 1830, Bernhard Heine (1800–1846) had already presented a flamboyant instrument, called *'osteotome'* which could be used to cut long bones [2]. The *'osteotome'* had a chainsaw with a chain which cut directly, i.e. without passing the chain behind the bone. This instrument was based on the idea that the chain run along a groove and was operated with a manual crank handle. The *'osteotome'* became very successful in Europe and was granted an award by the Academy of Sciences of Paris in 1835. This instrument, which was invented to cut long bones, was used in cranial surgery. However, in spite of its advantages, it did not become a routine instrument due to its high price, complexity and type of cut: from outside-inward. The instrument was too large and uncomfortable. The surgeon required a harness to use it. Heine, its inventor, was a German physician who was interested in bone formation and repair. He was the first person who recognised the importance of the periosteum during bone regeneration. At the end of the nineteenth century there were some designs of chainsaws which were coupled to a crank handle system that moved them continuously, just like the pedals of current bicycles. However, these designs also had a low impact on cranial surgery.

We can affirm that, at the dawn of craniotomy, all methods of bone cutting that had been experimented were dismissed when the braided or twisted Gigli's saw was introduced and its use became popular. Leonardo Gigli (1863–1908) was the inventor of the legendary saw, named after him [3]. The saw cut the skull from inside-outward once it had been passed underneath it through two holes. It was initially a threaded steel saw with a thickness of 1 mm and a very small thread pitch. It had handles on both edges that allowed to fix some handgrips to use it. These saws were very fragile and broke easily, particularly if the approach angle when cutting was very acute. For this reason, it was advisable to cut with the saw in a flattened position and an open approach angle. In any case, due to its low price, it was recommended to have several saws for each procedure and replace them in case of breaking or damaging them. The saw was soon made by twisting two steel wires. This allowed to improve both the quality of the cut and its resistance to breakage.

The Gigli's saw had to be introduced under the bone between the skull and the dura mater, passing from one hole to another one. For this purpose, some guides were soon designed as flexible grooved probes. Once they had been introduced through the holes, they allowed sliding the saw between the probe and the skull, and cutting the bone before removing the guide, which now worked as a dura mater protector. These first flexible guides were made of whale bone but they were later manufactured in steel, like Marion's guides. However, they did not guarantee that the edge of the Gigli's saw, once it had been passed through the first hole, reached the second hole. For this reason, some bolts were later designed with the shape of non-deformable but flexible steel sheets with a thickened edge. They also had a small hook near such edge where one of the handles of each end of the Gigli's saw was fastened. The saw was then passed along with the bolt from one burr hole to another one. After passing the saw through the holes, the handgrips were fastened to the saw handles and the bone was cut. The bolt protected thus the dura mater. Ideally, the cut had to be bevelled to make it easier to connect the osseous flap once it was replaced after the surgery.

Although increasingly efficient bolts were designed, the main challenge of Gigli's saws was how to take them from one hole in the bone to another along the epidural space without accidentally breaking the dura mater and making them dip inside the subdural space, as this could damage the brain. They could not get out through the other hole or, if so, the dura mater would be broken when cutting the bone.

An alternative option to the bone saws to cut the skull bones was the bone-cutting forceps. These strong forceps were designed to cut small bones or bone pieces and some surgeons used them to connect the craniotomy holes. They were used as an alternative to the handsaw in some locations with a difficult access or when not requiring so much help from the assistant to restrain the head. The most used bone-cutting forceps were those with a grooved surface. For this reason, they are called gouge forceps. Special cutting forceps were designed for the skull. They had a fine and accurate cutting jaw so that they could be introduced between the bone and the dura mater. An initial model was patented in the United States in 1896 by Allen DeVilvis (1841–1917), a rural physician from Toledo (Ohio), who also invented an atomiser to fluidify the patient's throat. A Swedish surgeon called Karl Dahlgren (1864–1924) designed some similar forceps that cut the bone from inside-outwards in 1896. It became pretty successful for several decades and just like the previous one it allowed to make linear bone cuts thanks to its design and strength. However, it was commonly used to complete sections that had been done with a saw or to weaken the lower side of the craniotomy before the fracture. As the bone is cut with gouges by continuously biting it, it is possible to make a cranial opening with the size and shape expected. However, the reposition of the bone flat is not accurate.

In spite of the quick success of the osteoplastic craniotomy with holes and cutting the bone between them some authors kept on inventing alternative systems for cranial opening. A short-lived example was the *'craniotome'* designed by the Italian inventor Alessandro Codivilla (1861–1912). This instrument allowed lifting a circular piece of bone of the size they wanted. The system had two pieces. One was firmly fixed to the skull in the centre of the craniotomy. On this piece a movable arm with a vertical bone-cutting needle was coupled. This way, when whirling around the arm, the needle made an increasingly deep groove on the bone until it was completely cut. Codivilla was born in Bologna, where he worked and developed innovating techniques concerning limb traction.

28.3 High-Speed Motors for Cranial Opening

Nowadays craniotomy is carried out with high-speed motors (up to 100,000 rpm) with coupled pieces that allow both drilling and cutting the bone. These motors have a pneumatic or electrical supply. The equipment has a small and ergonomic hand piece which can be manually operated and contains the motor itself. In pneumatic motors, a hose allows to connect the motor with the pressurised gas supply. A manometer is put in between them to control the output pressure and keep it constant. In electric motors, a cable runs towards the control panel, where several parameters can be managed, such as the spinning speed, direction of rotation and acceleration and deceleration speeds. In both cases the motor is controlled by a pedal. This pedal is put in between the motor and the manometer in pneumatic motors. It allows a higher or lower speed, depending on the pressure exerted with the foot. The mechanical factors to be considered in modern motors are the spinning speed, which is measured in revolutions per minute (rpm), the torque or force needed to rotate an axis and which physically has to do with the moment of a force and is measured in newtons per metre, and power, measured in horsepower. Another element that is highly appreciated in modern motors is ergonomics. It is related to the shape, size and weight of the motor and determines the ease of use, accuracy and fatigue of the surgeon.

A series of accessories and workpieces are coupled on the edge of the motor with secure and fast coupling and uncoupling mechanisms, depending on the intervention the surgeon wants to carry out. Cranial drilling can be carried out in two ways: with perforator devices or with burr drillers. Both have been previously described. The perforator attachment device is only useful when operated at a low spinning speed, around 1000 rpm. For this reason, in some equipment it is necessary to place a piece that slows the speed at the end of the motor. The perforator is mounted onto this driver. Burrs work with high speed and are far more delicate, versatile and ergonomic. Both systems allow making as many holes as required for the designed craniotomy. A vertical-cutting saw is now placed on the motor, set in the high-speed way. The motor has an accessory with a foot-shaped protector to prevent the dura mater from being unintentionally cut with the saw. The foot also allows fixing the distal end of the saw so that it does not become bent. It is necessary to separate the dura mater on the edges from the bottom of the hole with a dissector and place the foot-shaped protector between the dura mater and the internal table before starting the cut, which will be made in a straight or curved line towards the next hole, where the procedure is repeated until completing the craniotomy. It is possible to carry out a craniotomy with a single hole, where the cut of the bone starts and ends. Once the craniotomy has been completed, the bone flap is lifted by just moving the fragment with dissectors and carefully separating the dura mater from the internal table.

The high-speed motor is also useful in other stages of the neurosurgical approach. The space between two holes cannot be often cut with the vertical saw as there are internal osseous crests. This also happens in pterional or medial suboccipital craniotomies. In those cases, the bone fragment is lifted by levering it. To make this procedure easier it is advisable to previously weaken this segment by milling the outer table and the diploe. This piece is later fractured by means of more powerful dissectors or lifters. On exceptional circumstances it is not recommended to cut with a saw or fracture the bone between two holes. This happens above the dural venous sinuses. In these cases, the bone cut is carefully made with the burr or a fine punch, although the cut with a vertical saw is normally safe. The internal edge of the craniotomy is homogenised with a spherical burr. The spherical burr is also used to enlarge the craniotomy in those areas where it is not possible to cut with the saw. This is common in pterional craniotomies and, in general terms, in all those craniotomies involving the base of the skull. High-speed motors are useful not only to make and complete craniotomies, but also during the intracranial stage, in which they have become essential for surgeries of the base of the skull to resect specific osseous fragments invaded by a tumour or to create specific corridors. This happens when performing anterior clinoidectomy, opening the internal acoustic meatus or resecting the suprameatal crest. The motor is also frequently used to make small holes on the edge of the craniotomy during the surgical closure. This aims to create passage holes to lift the dura mater with fine stitches.

28.4 Other Instruments Used in Cranial Surgery

Considering the security, size and versatility of the cranial openings made by means of craniotomies it is logical to think that cranial openings made by trephine-serrated crowns were no longer interesting. The design of trephine crowns was not modified at all in comparison with those used until the end of the nineteenth century, which have been described in the previous chapter. They became a residual technique that rapidly faded until it was forgotten. As a residual instrument of historical value, we must highlight the Scoville trephine. It had a hollow cylindrical crown with serrated edges, a central pin and a security system concerning the depth of the cut by means of a peripheral crown or a toothless sliding cap on the edges. This crown was connected to a Hudson brace handle to carry out a manual intervention or to a motor driven with an electric or air low-speed motor to carry out a motorised intervention. This modern design of a trephine with a large diameter was created by the American neurosurgeon William B. Scoville (1906–1984), who also invented an aneurysm clip with a spring. The regular diameter of the crown was 1¾ inches, i.e. about 45 mm. Smaller crown diameters are not efficient for any complex intracranial procedure and larger crown diameters are very uncomfortable and difficult to work with during the drilling procedure on the skull. The trephine was useful to make cranial openings on the convexity with simple scalp linear cuts. Consequently, it was useful to evacuate epidural haematomas or brain cortical or subcortical lesions that were well delimited. A perfectly circular disc of bone is obtained with the trephine. Once the intervention is over, it can be easily replaced back to its original position and eventually secured with cranial fixers.

A routine procedure before craniotomy consists of separating scalp soft tissues from the bone. The deepest layer of these soft tissues under the galea aponeurotica is the periosteum that covers the bone of the cranial vault. The instrument that allows detaching the periosteum from the bone and separating it therefrom, just like a scraper, is called 'periosteal elevator'. This instrument is called '*periostotomo*' in Spanish and *'rugine'* in French. These instruments were made of steel and had one enlarged end with a bevelled edge which slightly bent when compared to the axis of the instrument. The shape and the size of the enlarged end could be very variable.

A series of unsophisticated and powerful instruments are sometimes necessary in bone and cranial surgery to cut or carve the bone by tapping with a heavy mallet on the handle of such instruments. Most of these instruments were previously used in craftwork such as carpentry or masonry and adapted to surgical activities. These instruments have been used throughout the history of surgical cranial opening. The names of these instruments are confusing. The terminology is often misused, although it is true that the final result is very similar.

The scalprum (from Latin '*scalprum')* is a metal instrument that has a handle and a blade with a bevelled end. It is used in osseous surgery to carve the bone by tapping with a bone mallet or hammer. The chisel (from anc. French *'cisel'*) is a 20–30 cm tool with a steel, straight, double-bevel tip which allows carving the bone by tapping with the hammer or the mallet. The gouge (from later Latin '*gu[l]bia'*, word of Celtic origin, cf. Middle Irish '*gulba'* 'bird's beak') is a chisel with a half-round blade that has a bevelled end. It is mainly used in osseous surgery to carve curved surfaces. The cutting edge of all of these instruments allows to use them not only as bone-cutting instruments but also as scrappers or periosteal elevators and, due to their hardiness and bevelled end, as bone fragment lifters.

Bone lifters are short and strong instruments that are specifically designed to lift fragments of fractures or bone flaps by passing them under the free osseous fragment and levering from the solid side. If the groove is small, it must be enlarged with bone-cutting forceps, a saw or a trepan.

A particular instrument in neurosurgery is the dissector, which must be differentiated from the dissecting forceps. The neurosurgical dissector is a delicate steel instrument that has in both ends a bevelled enlarged area with a variable shape. It is always smaller than the previously described instruments. They are particularly useful in craniotomies to separate the dura mater from the cranial bone. The dissecting forceps are used in general surgery. They have a handle that is articulated in the centre and allow the surgeon to dissect tissues by separating or piercing them. It usually has a curved tip, which is more or less angled, to separate tissues (just like when opening a pair of scissors) or pierce them with the blunt point when the grips are closed. The dissecting forceps are not used in cranial surgery.

Carrying out a craniotomy requires a certain amount of general surgical material. As the main problem of the skin incision of the scalp is a profuse bleeding of the pericranium, cranial surgeons have always been concerned about controlling this issue. Direct haemostasis of the bleeding points was done by cauterising, pressing or ligation. Finally, haemostatic forceps (which had countless designs) were introduced. Thierry de Martel (1875–1940) invented a pair of T-ended forceps to be applied on the galea of the pericranium flap. The most successful model was the legendary haemostatic forceps invented by Walter Dandy (1886–1946) and characterised by its lateral curvature. These forceps allowed to close bleeding points or to make a preventive haemostasis by inserting them regularly on the galea aponeurotica. They could adapt to the surface of the head thanks to their lateral curvature. An alternative strategy to guarantee haemostasis was the preventive haemostasis methods such as tied elastic bandages around the head, transfixion sutures parallel to both sides of the incision, infiltrating of the margins of the incision with saline with or without epinephrine or applying of compression staples on the margins of the incision (like the popular Raney clips, which were metallic at first but later were made of plastic and became disposable). We no longer use haemostasis forceps or clips since we do haemostasis with fine bipolar coagulation forceps.

28.5 Surgical Instrument Catalogues

An interesting historiographical methodology to know the instruments used for craniotomies consists of studying the surgical material catalogues [4, 5]. At the end of the nineteenth century the manufacturing, distribution and sale of surgical material were already a business activity.

Surgeons initially designed their own surgical instruments at that time and ordered the manufacturing thereof. The advertising activities of the manufacturers specialised in surgical instruments initially focused on hospitals, but the increasing number of professionals and their geographical dispersion forced them to change their strategy. Hence, they started including catalogues of medical/surgical instruments at the end of medical texts with up to three or four pages. The first advertisement inserted in a medical text can be found in John Woodall's (1570–1643) work entitled '*The Surgeon's Mate*', which was published in 1617 [6].

At the end of the eighteenth century European companies already used different press advertising techniques, even what we nowadays call 'merchandising', with messages shown on buttons, belts or boxes. S. Laundy, a manufacturer of surgical instruments from London, published his first known list of surgical supplies without illustrations in 1775 with the aim of advertising his business. It is assumed that the first illustrated catalogue of surgical instruments was created by J.H. Savigny. It was probably published in London in the year 1798 under the title *'A collection of engravings, representing the most modern and approved instruments used in the practice of surgery, with appropriate explanation'*. Savigny was a surgical material manufacturer who worked under the surgeon's orders.

Catalogues were later published in a book format with an increasing number of pages [7–9]. Just like in medical books, instruments were initially illustrated in distinctive pages. The illustrations started being merged with the text from 1860 on and the quality of the drawings improved. Manufacturers engraved the names of their companies on the instruments. The name of the company also appeared in the models shown in catalogues because many medical texts included the instrument illustrations taken from the catalogues among their images. A later improvement was including the registered names, prizes and reference numbers of each instrument in the catalogues. This way the catalogue became a business information system and allowed the surgeon or the hospital to order the material (Fig. 28.3). Colour pictures were included at the beginning of the nineteenth century and catalogues started being translated into other languages. This is how the competition between the products manufactured in Germany, the United Kingdom and the United States started.

The reason for studying catalogues is because they include both information and illustrations

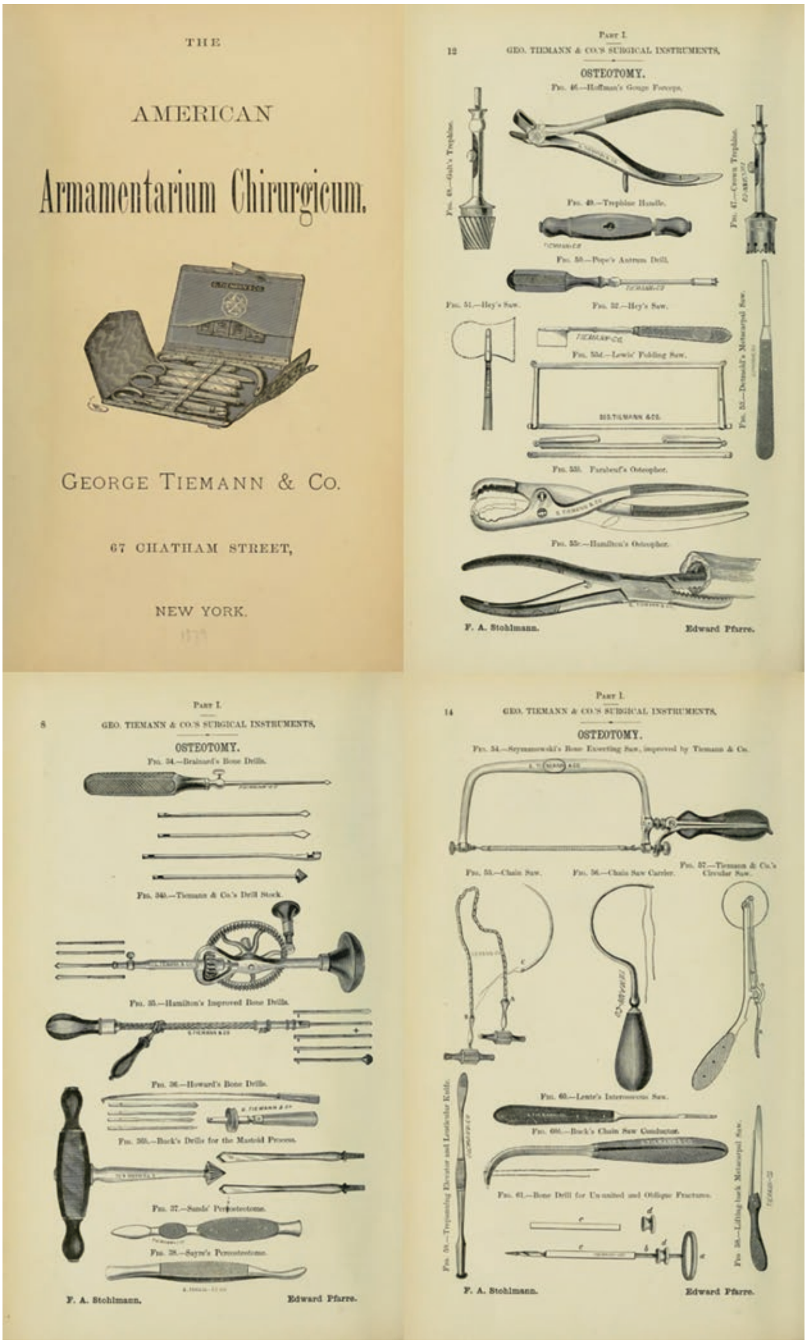

Fig. 28.3 George Tiemann's catalogue of surgical instruments published in New York in 1879. The instruments of trepanation, amputation and osteotomy are illustrated together in the following pages: Page 8: A large number of bone drills and drills are shown, mounted on straight, T-handle or brace handles. Page 12: A trephine handle (Fig. 49), a cylindrical trephine (Fig. 47) and a truncated cone trephine of Galt (Fig. 48) are illustrated, together with Hey's saws (Figs. 51 and 52), bone forceps and a drill for a mastoid antrum (Fig. 50). Page 14: In this page we highlight the chain saw (Fig. 55) with a saw carrier (Fig. 56) for cutting long bones, and a circular saw (Fig.57). Page 18: Again, to highlight a different type of circular saw (Fig. 66). Page 20: A brace trepan handle with guarded crown (Fig. 72) and a trepan handle for guarded trephines (Fig. 75), along with several periosteal elevators. Page 22: The Heine's saw or osteotome (Fig. 78). Page 24 recalls a large number of bone forceps, elevators, osteotomes and hammers

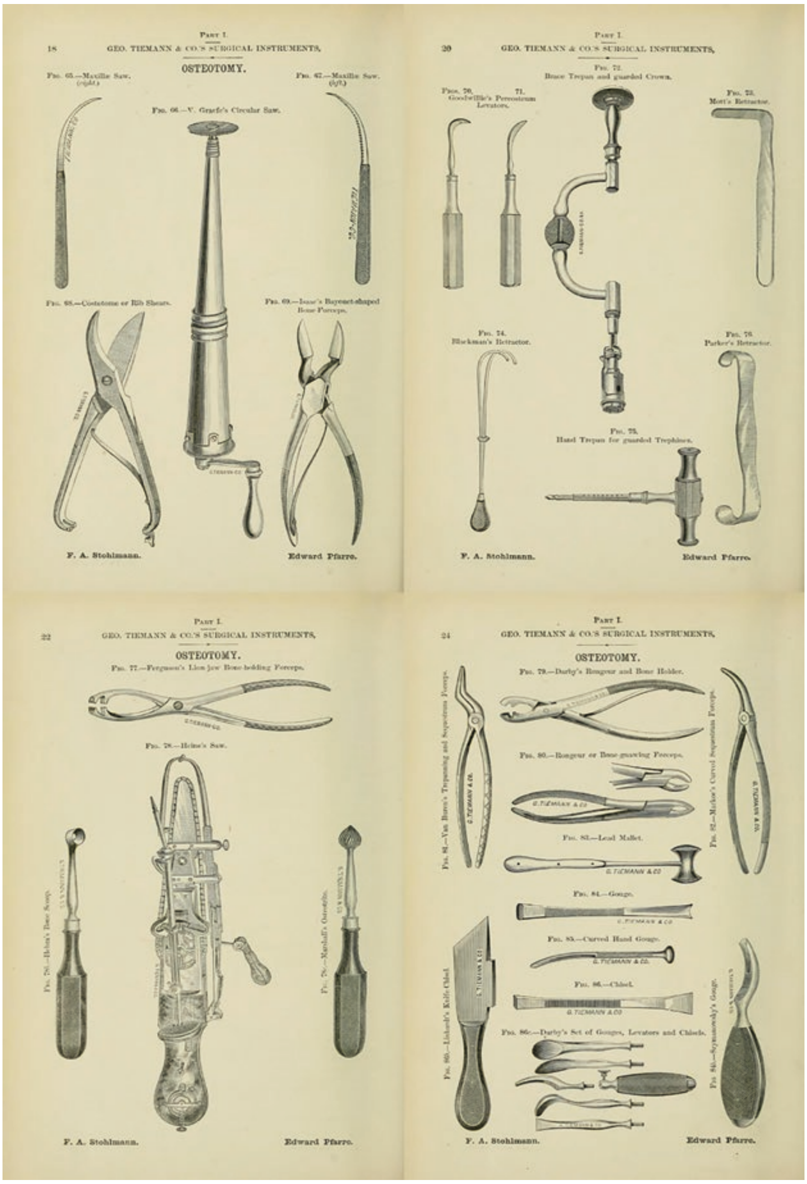

Fig. 28.3 (continued)

about the surgical instruments used by the time they were published. We must consider that it took a while to add many new instruments to the catalogues. Many others were included for a long time (although they were not used very often) until they stopped selling and manufacturing them and became discontinued. Catalogues in book format have been disappearing in the last years whereas those in digital format that are available on websites are becoming more popular. In addition to catalogues, many books and works that assess the surgical instruments of that time or throughout history have been published. We must highlight the book published by Charles Truax at the end of the nineteenth century, particularly in 1899 [10]. It was entitled *'The mechanics of Surgery'* and assessed the instruments and surgical/medical material and supplies of that time. We must not forget either the series of articles written by John Kirkup, which were published in 1983 in the medical journal *Annals of the Royal College of Surgeons of England* [11]. These articles include a comprehensive historical review of surgical instruments.

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29 Initial Development: Manual Osteoplastic Craniotomy

The evolution of the craniotomy can be divided into two phases, if the surgical technique itself is considered. In the first phase a pedicle bone flap was raised, that is, attached to the pericranial soft tissues, such as muscle and scalp. In a second phase free bone flaps are raised, that is, separated from any attachment to the pericranial soft tissues. For the perforation and cutting of the skull bone to make the craniotomy, both manual and motor instruments have been used, the description of which we have described in detail in the previous chapters. It is not possible to chronologically follow together the changes in the surgical technique and in the instruments, since there have been great lurches. Therefore, we are going to separate the manual cranial opening from the cranial opening aided by motors. The first will be discussed in this chapter and the second in the next one.

29.1 Manual Osteoplastic Craniotomy with Pedicle Bone Flap Using Bone Forceps

As an alternative to the use of manual saws to cut the bone between the holes, some well-known surgeons kept on defending the idea of cutting the bone with a chisel or bone-cutting forceps, either in a general way for all their craniotomies or just for some of them, particularly those concerning the posterior fossa or temporal fossa. This was due to the difficulty regarding the safe use of the bone saw in the operative field. Many authors showed a firm position defending the use of bone-cutting forceps for many years which sometimes were well argued and based on positive surgical results.

An example of this type of attitude that clung to the past was represented by Fedor Krause (1857–1937). Krause was a wonderful surgeon who was born in the province of Silesia and studied in Berlin. He wrote several impressive works about brain and cranial neurosurgical pathology, such as *'Chirurgie des Gehirns und Rückenmarks'* in 1907, *'Chirurgische Operationslehre des Kopfes'* between 1912 and 1914 and *'Die allgemeine Chirurgie der Gehirnkrankheiten'* in 1914, which were translated into French and English. His works included a great deal of illustrations with prints that showed all cranial approaches of that time that used osteoplastic craniotomy with pedicle flap, from cerebral hemisphere approaches to those concerning the base of the skull, including the pituitary and pineal glands, and those regarding the temporal and posterior fossae. Krause is an example of a superb surgeon but anchored in classic believes and techniques. Krause was very critical with the electric instruments. He did not recognise any advantage concerning the use of the Gigli's saw either. He was in love with the chisel and the mallet, and particularly with the bone-cutting forceps (Fig. 29.1).

J. M. González-Darder, *Trepanation, Trephining and Craniotomy*,
https://doi.org/10.1007/978-3-030-22212-3_29

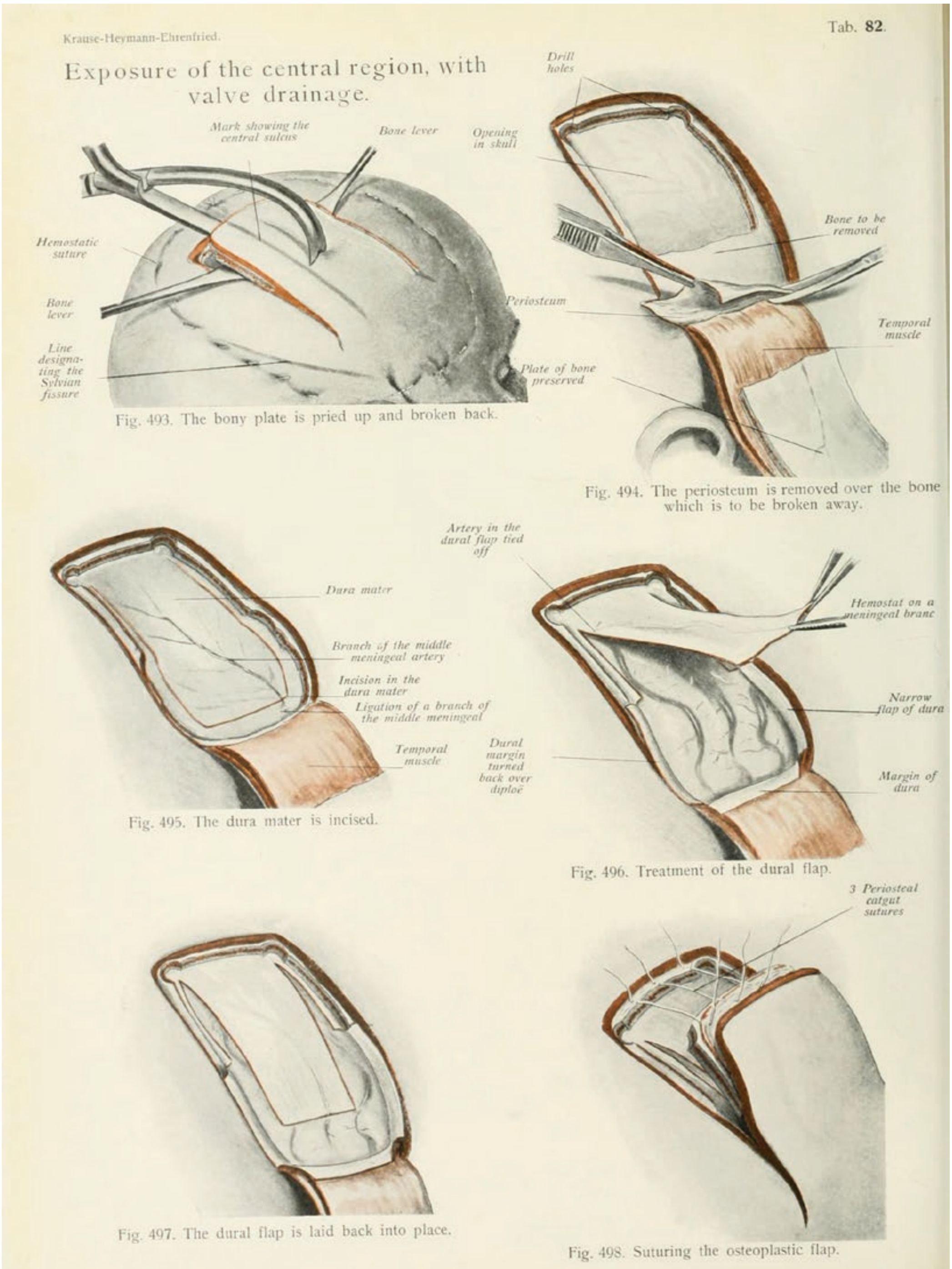


Fig. 29.1 Surgical technique of different types of craniotomy by Fedor Krause. The figures of Tab. 82 show the steps of the osteoplastic craniotomy for exposure of the central region. The fracture of the base of the bone flap is done with a lifter and using its own original design clamp. After the elevation of the bone along with the scalp, some additional bone is removed to expand the access and decompress. Tabs. 85, 89 and 91 represent some craniotomies for tumours and hemispheric lesions. Tabs. 95, 97 and 100 show different posterior fossa craniotomies; Tab. 100 a craniotomy for a depressed bony splinter; and, finally, Tabs. 52 and 54 a craniotomy for resection of the Gasser ganglion and third trigeminal branch (Krause F, Heymann E, Ehrenfried A. Surgical operations of the head. New York: Allied Book Company; [1])

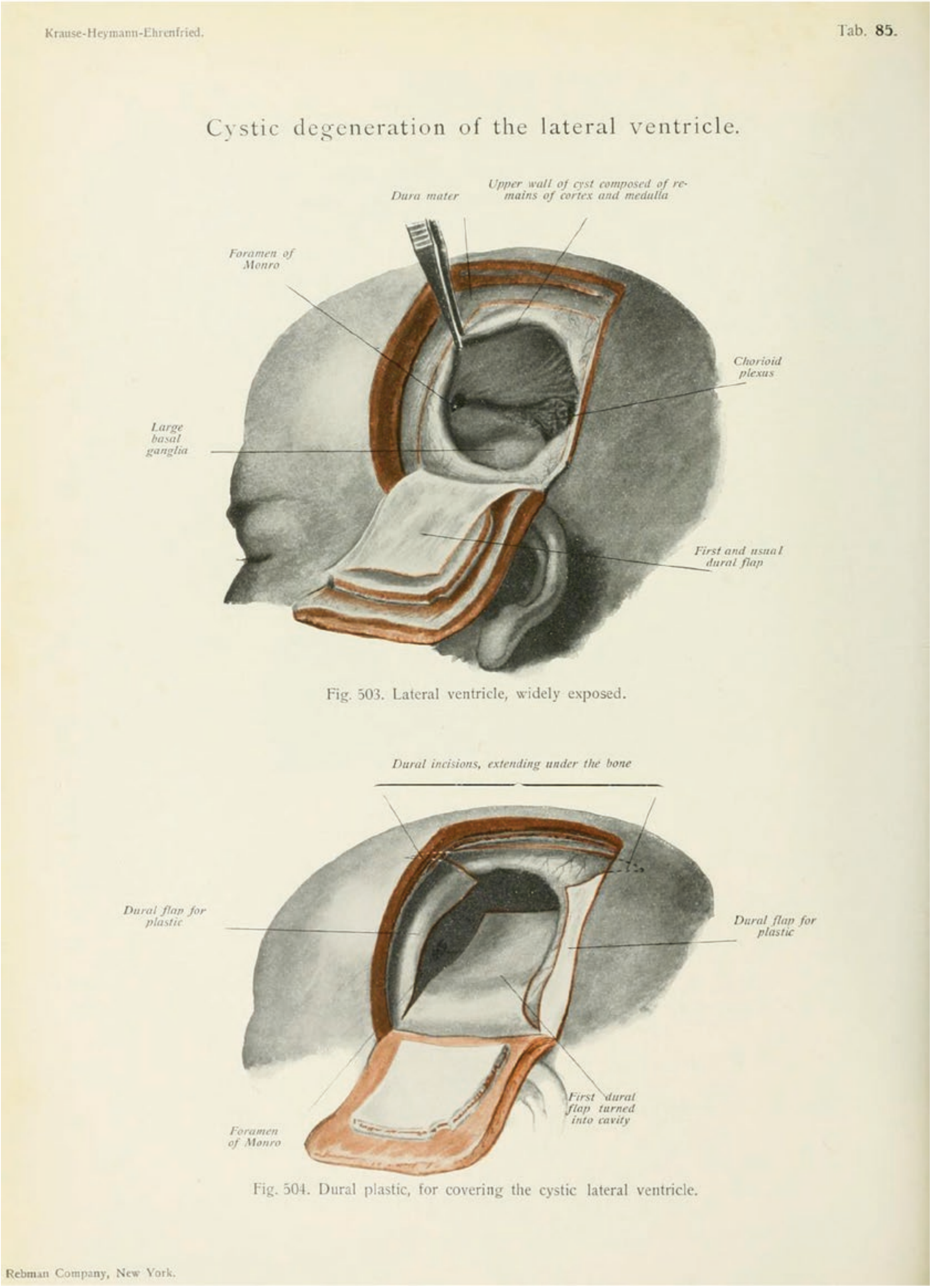


Fig. 29.1 (continued)

Krause-Heymann-Ehrenfried. Tab. 89.

Extirpation of a tumor of the frontal region, Plate A.

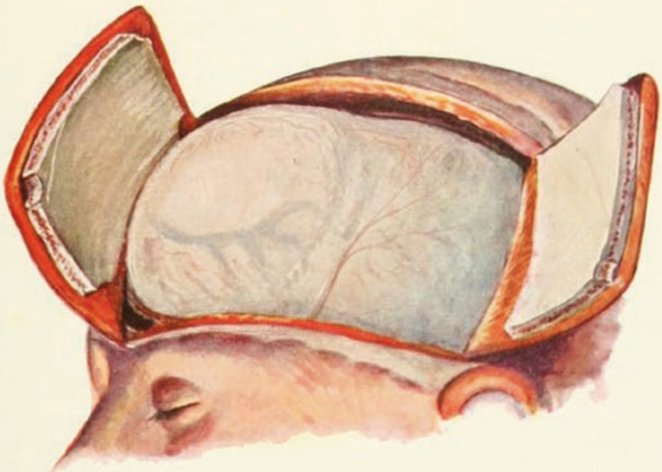


Fig. 521. Double trap door, necessitated by the large area to be exposed (first stage of operation).

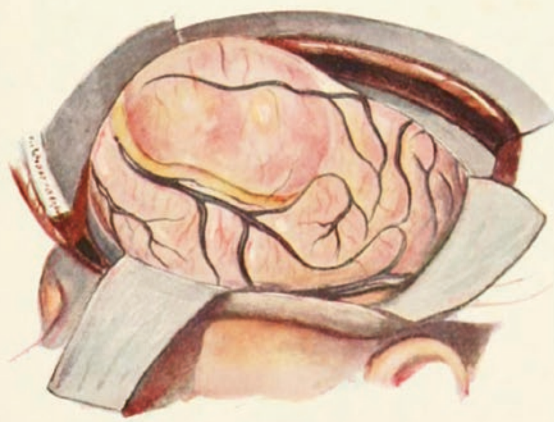


Fig. 522. Formation of two dural flaps (downward and backward).

(The pia-arachnoid has been incised at lower margin of tumor.)

Fig. 29.1 (continued)

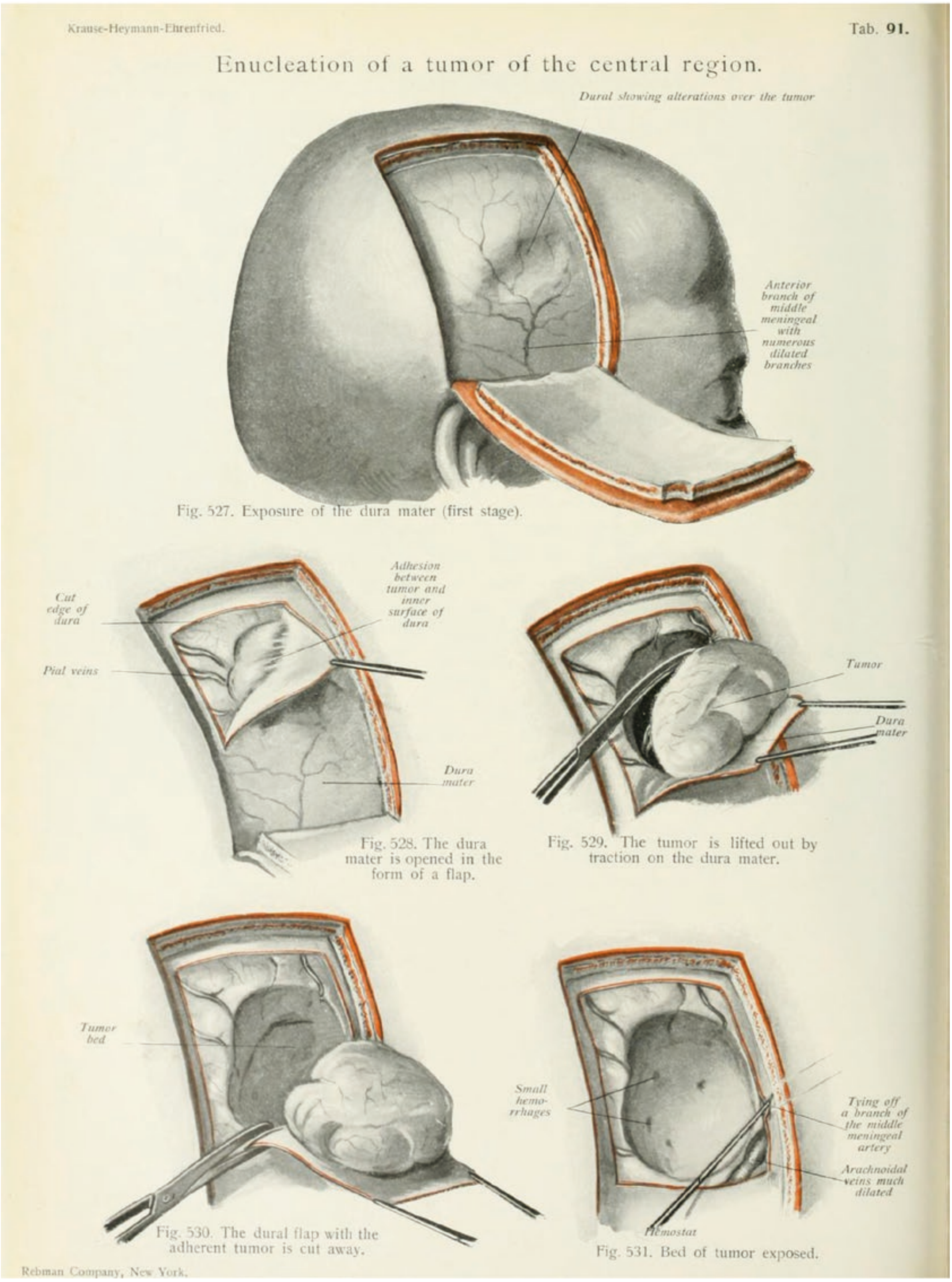


Fig. 29.1 (continued)

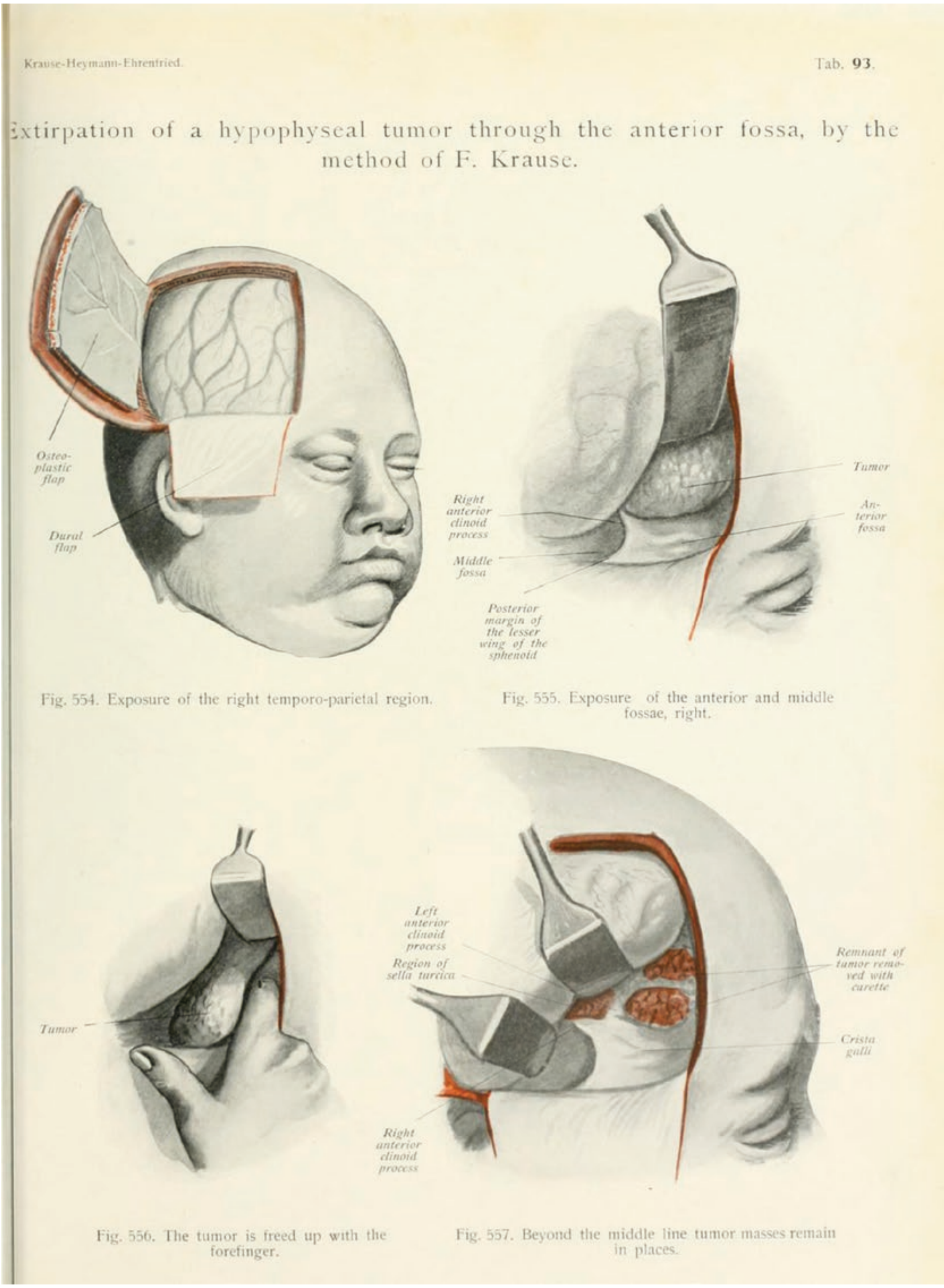
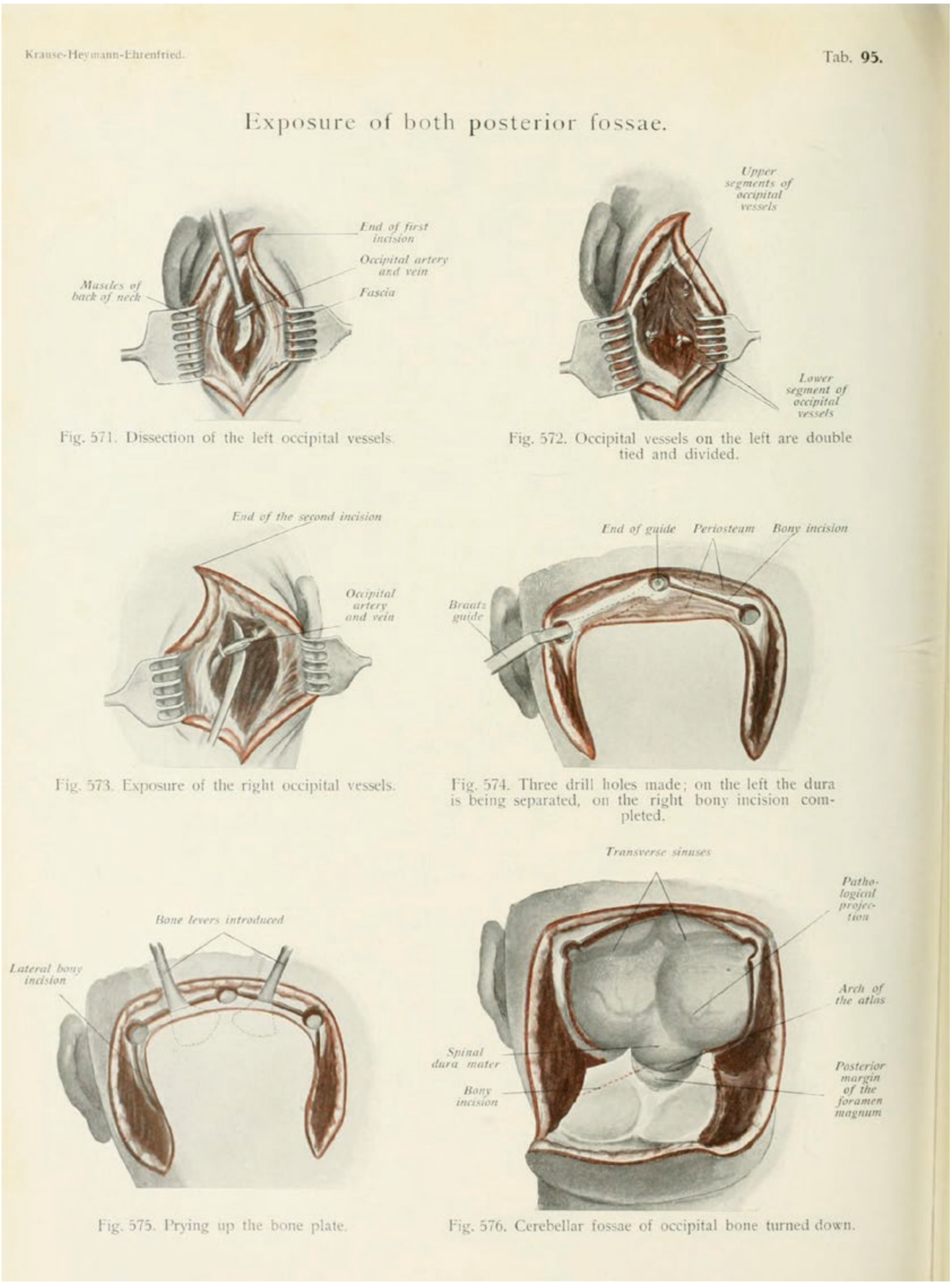


Fig. 29.1 (continued)



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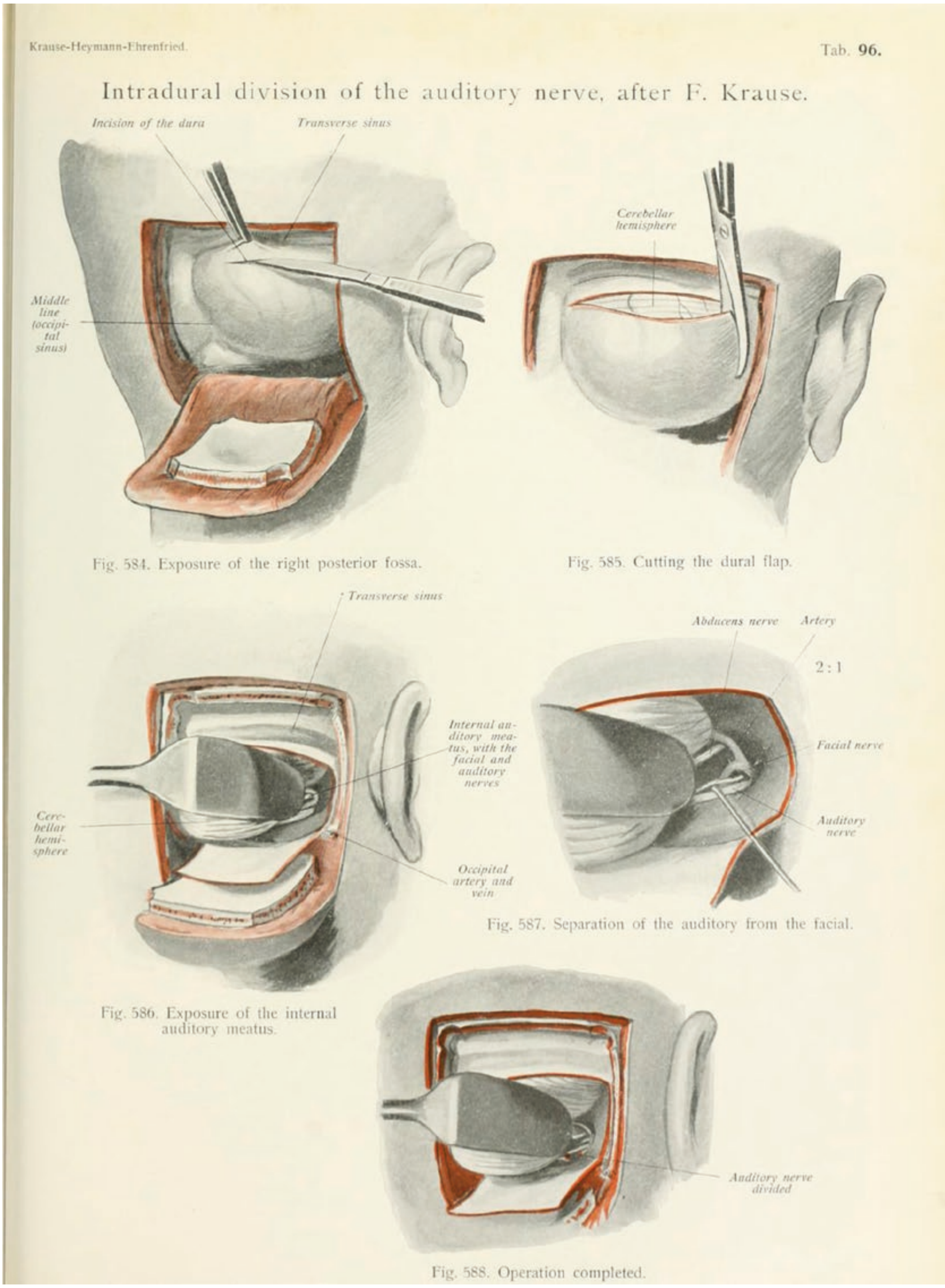

Fig. 29.1 (continued)

Krause-Heymann-Ehrenfried. Tab. **97**.

Enucleation of a tumor of the cerebello-pontine angle.

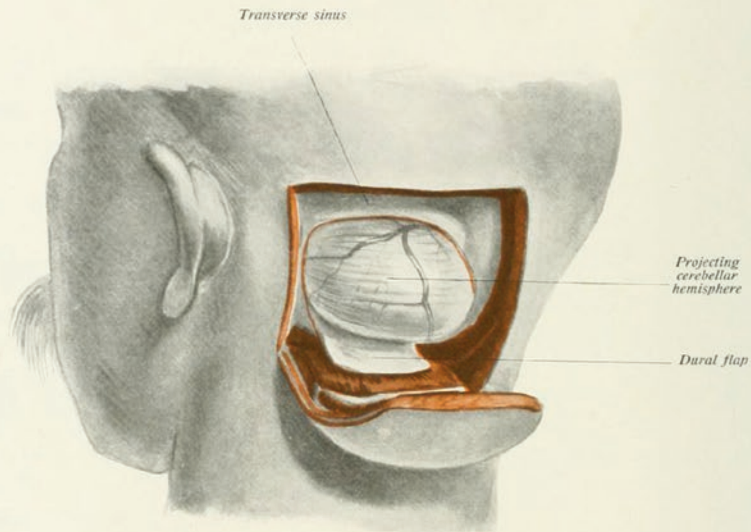

Fig. 592. Exposure of the left cerebellar hemisphere.

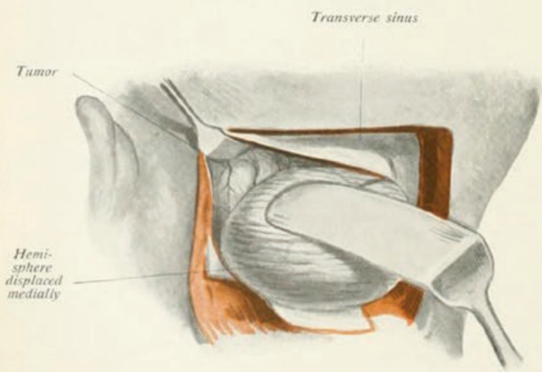

Fig. 593. Exposure of the tumor.

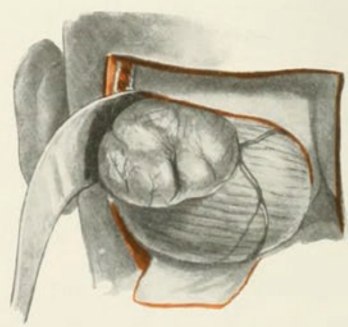

Fig. 594. Enucleation of the tumor with a large dull curette.

Rebman Company. New York.

Fig. 29.1 (continued)

Extirpation of a tumor in the region of the vermis.

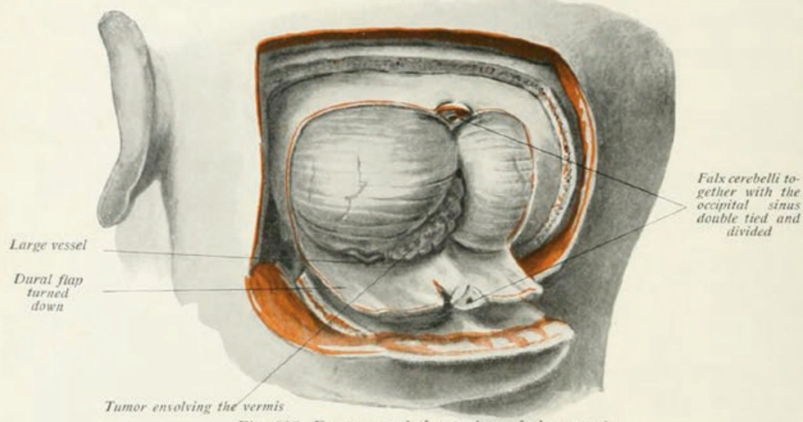

Fig. 605. Exposure of the region of the vermis.

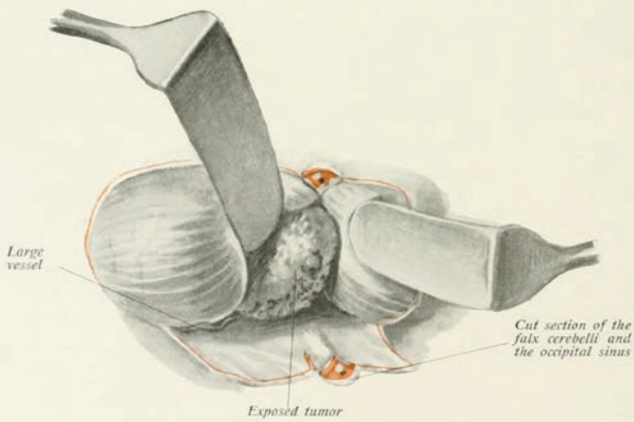

Fig. 606. The tumor is isolated.

Fig. 607. The wide exposure of the fourth ventricle following the extirpation.

Fig. 29.1 (continued)

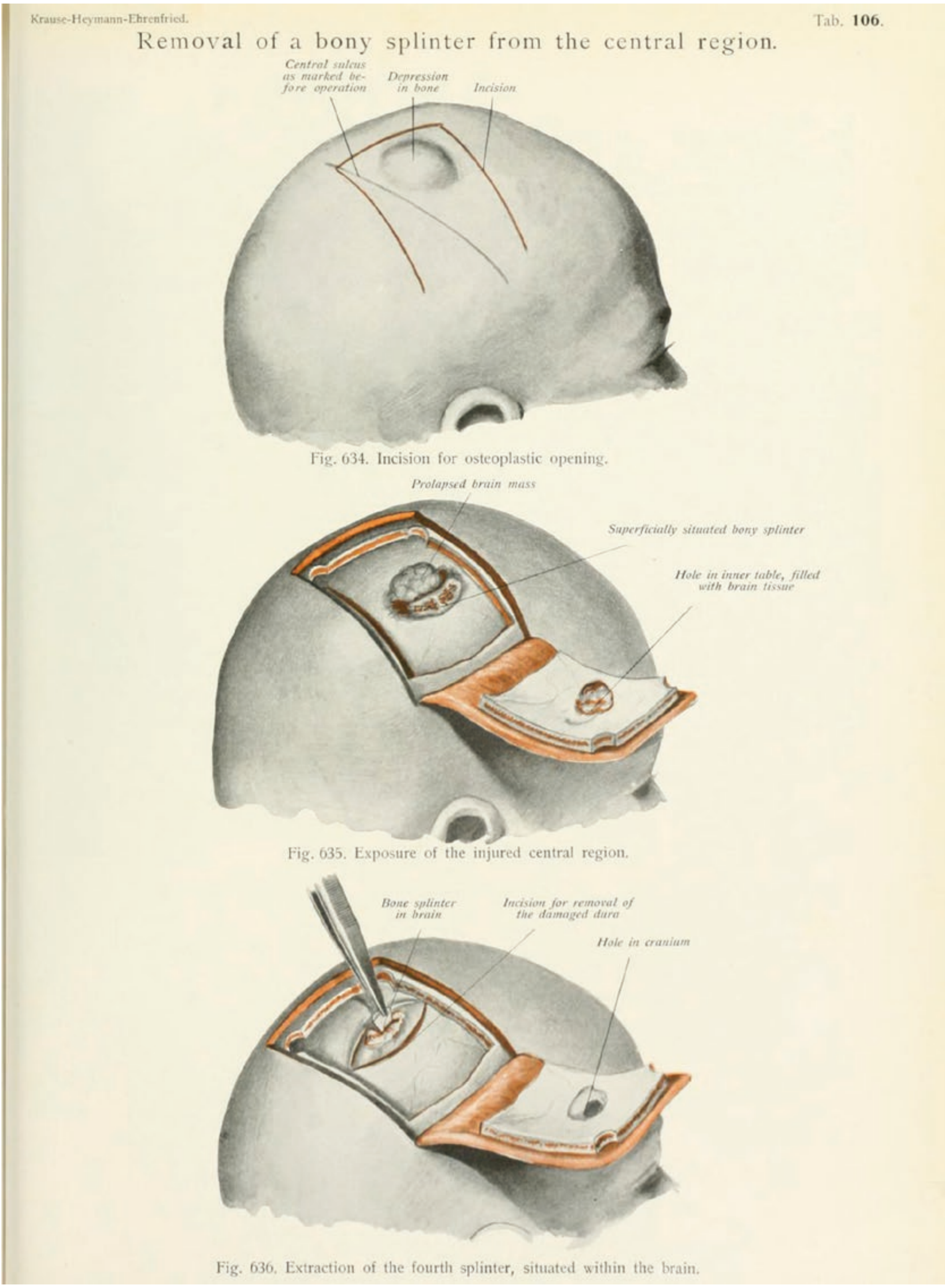

Fig. 29.1 (continued)

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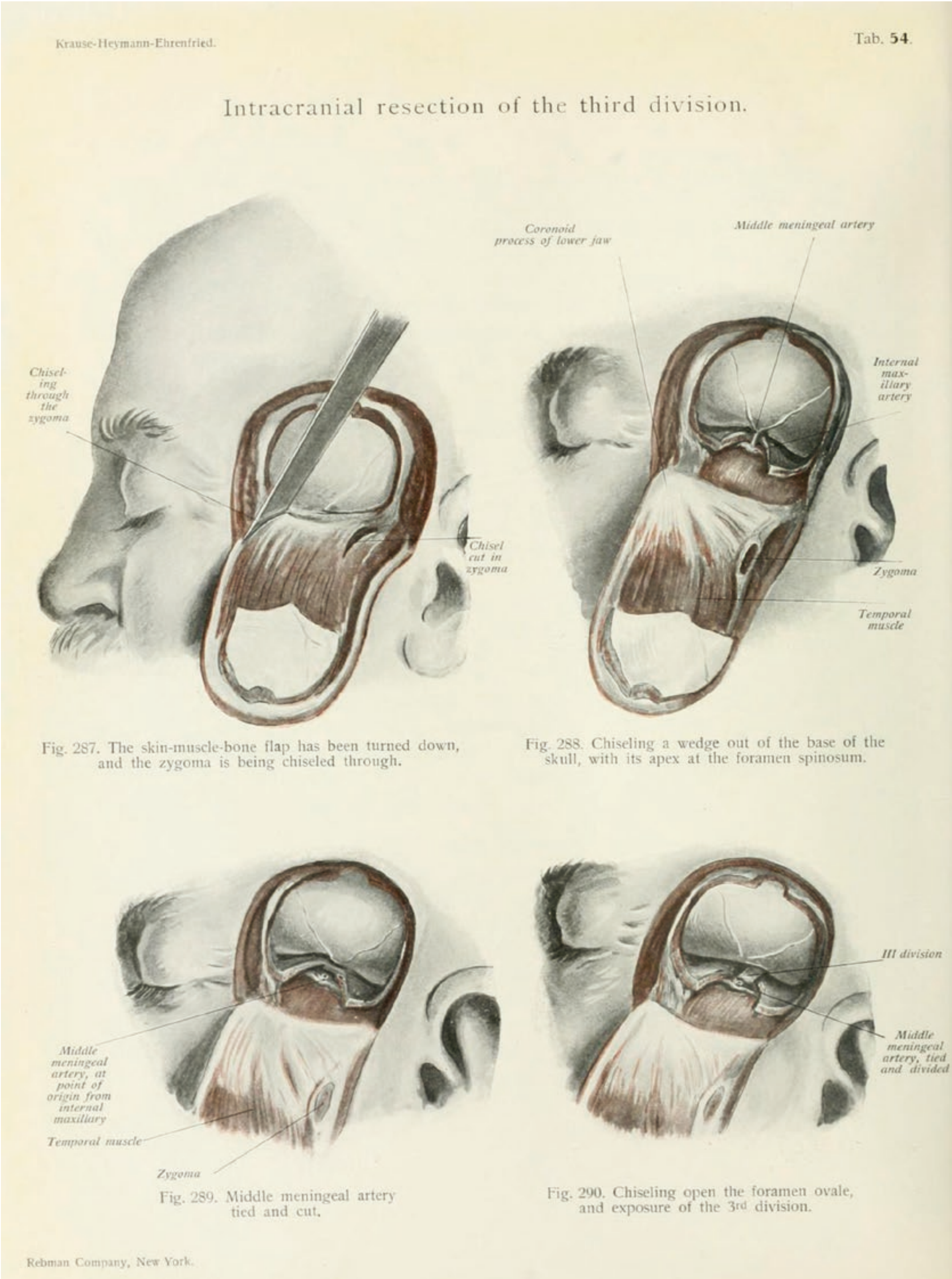

Fig. 29.1 (continued)

He remembered that the craniotomy was initially made with the chisel and the mallet and claimed its value. This opening is easy, versatile and useful in those cases when there are no other instruments, such as in emergencies. The tapping must be careful and tangentially orientated. This allows to minimise the unavoidable vibration of the hammering, which involves some risk for the brain. Once the bone had been sectioned the bone flap is lifted by levering and fracturing the base. If the base is too solid it can be weakened by two other burr holes or by using Doyen's grooved chisel.

Krause described in detail his personal technique to carry out a parietal temporal osteoplastic craniotomy in his *'Chirurgie des Gehirns und Rückenmarks'* in 1907 [1]. The surgical technique and the general management of the patients are full of old-fashion proposals, even at that time, that he strongly defended. He pointed out that he preferred local anaesthesia rather than general anaesthesia with ether or chloroform. The subcutaneous injection of a novocaine-epinephrine solution along the planned incision was enough to control the pain and the haemostasis. This way, as Krause says, it is only necessary to compress some pericranial arteries. The preventive control of pericranial bleeding can also be made by the Heidenhain haemostatic suture. It consists of applying a continuous parallel suture 1–2 cm far from the incision. Its depth reaches the bone or the muscle in the posterior fossa approaches and it is left 8–10 days after the surgery. The problem concerning this suture is the ecchymosis and peripheral oedema, which lasts a few days. He also described the use of some haemostatic forceps, such as the Péan T forceps or the Makklas clamps. However, he emphasised his preference about the local anaesthetic's injection or otherwise the previously described haemostatic suture. The incision on the soft tissues is directly made until reaching the bone, which is only denuded in both angles where the burr holes are going to be made.

For craniotomy, he used the brace handle with a lancet driller to start making the holes. When the dura mater was exposed and visible he substituted the lancet by a spherical burr with a diameter of 10–13 mm. After separating the dura mater, the bone between the holes was cut with the Dahlgren rongeur forceps. He affirmed that the bone-cutting forceps were always enough excepting in those areas where the skull was very thick, such as the external occipital protuberance, where he recommended using the chisel and mallet.

Krause preferred manual instruments rather than electric ones both for making the holes and cutting the bone. Krause was also critical about the Gigli's saw. In his opinion, the only advantage when compared to Dahlgren rongeur forceps was that the saw allowed to make a bevelled cut in the bone, which made it easier to replace the bone flap when closing the skull and prevented it from dipping inside the skull. He argued that this could also be done with Dahlgren rongeur forceps, but not in such a clean and effective way.

Once the bone had been lifted, the periosteum was separated from the base about 1–2 cm to boost its dislocation. For this reason, the basal incision must extend beyond the cut margins of the bone. As there is a risk that the bone accidentally separates from the soft-tissue flap during this dislocation movement or the intervention, Krause designed some forceps to prevent it.

These types of cranial openings with chisel, hand saw or gouge forceps were definitively dismissed towards the use of the Gigli's saw in spite of the academic or scientific status of the surgeons who supported them. An exception to this general rule was the suboccipital craniotomy carried out along decades enlarging one or two burr holes. This technique continued being carried out this way worldwide until the 70s of the last centuries. Charles Harrison Frazier (1870–1936) represents the origins of this proposal. Frazier was a great American neurosurgeon who systematically carried out the osteoplastic craniotomy with a Gigli's saw. However, he preferred to perform a craniectomy with a chisel and a mallet in the posterior fossa as he considered that it was more beneficial for the patient. The suboccipital osteoplastic craniotomy with Gigli's saw was a formidable surgery. The craniotomy required to detach as a whole all soft tissues and nuchal muscles together with the occipital bone by means of a large horseshoe-shaped incision, which sectioned both occipital arteries and suboccipital nerves of Arnold. Several drills were done to cut an occipital bone flap attached to the soft tissues. The huge cutaneous-muscle-osseous flap was turned caudally to expose the dura mater of the posterior fossa. In front of this rudimentary craniotomy, the suboccipital craniectomy removing the bone was much less aggressive. It involved a T-shaped or linear skin incision and a midline way across the nuchal ligament, which is almost avascular, to the occipital bone. Once the bone had been denuded bilaterally, a burr hole was made in each occipital squama. Finally, burr holes could be enlarged as much as necessary by the gouge forceps or chisel. The bone defect left at the end of the surgery was protected by the reposition of the thick soft cutaneous-muscular tissue flap.

Outside the craniotomy technique, but just to give us an idea of general management of patients undergoing cranial surgery at that time, we are going to discuss some other challenges and their solutions. Just like other surgeons of that time, Krause supported the idea that the intervention had to be carried out in two surgical times, unless there was any contraindication (for example with abscesses). The first surgical time ended with the opening of the skull and exposing the dura mater. The osseous-muscle-pericranial flap was replaced back to its original position and it was carefully sutured. The reason for a surgery in two times was mainly due to the important surgical aggression that a craniotomy involved in that time. Patients showed large lesions and were in a very bad neurological condition. The anaesthetics and general treatment methods were limited and dangerous. For this reason, the most common cause of perioperative death was a shock due to cardiorespiratory disorders. Therefore, the partial decompression allowed by the craniotomy was beneficial for the patient. Another source of problems was intraoperative bleeding, which was often of venous rather than arterial nature. As it was difficult to control it, it frequently forced to abort the procedure. The origin of the bleeding was the diploe and the venous channels of the bone. It was aggravated by endocranial hypertension, a poor venous drainage and insufficient pulmonary ventilation. Sir Victor Alexander Haden Horsley (1857–1916) was the first person to use sterilised beeswax to control this bleeding. However, a long list of solutions had been tried before. In any case, the only option concerning the haemostasis of a profuse venous bleeding was wrapping with gauzes and closing the wound. The second surgical time, regardless of whether it was planned or imposed, was recommended to take place after 6–8 days, although this could be adapted to their needs.

29.2 Manual Osteoplastic Craniotomy with Pedicle Bone Flap Using the Gigli's Saw

All these attempts to improve the basic technique of craniotomy that had been described by Wagner using either manual or powered devices ended when the use of the Gigli's saw became popular. Alfred Obalinski (1843–1898) suggested the use of the Gigli's saw in 1897 to connect in pairs the burr holes and lift the osteoplastic pedicle bone flap [2]. However, the most important figure fuelling osteoplastic craniotomy with Gigli's saw was Harvey Cushing (1869–1939), who opposed to the use of either the chisel or the mallet and electric saws due to their potential harming effect on the brain as they might transmit the energy or the vibes. He advised also against the use of manual or electric circular saws of that time, which cut from outside-inward, due to their probable harming effect on the dura mater and the brain.

Leonardo Gigli (1863–1908) was an Italian obstetrician who worked in the by then German town of Breslau (nowadays the Polish town of Wroclaw). He was trained in Florence, Paris and London and was concerned about avoiding the problems caused after pubic symphysiotomy in women. This technique was used in that time as a solution in complicated deliveries in cases of pelvic deformity and aimed to increase the diameter of the birth canal. The section of the pubic symphysis caused serious perioperative complications and led to a later instability of the pelvis.

For this reason, Gigli supported, improved and promoted the lateral pubiotomy which had less complications and eventually allowed an osseous fusion that avoided later pelvic instability. To do so, he slid a bolt with a bone chainsaw behind the pubic bone, some centimetres far from the middle line and cut the bone. A contention bandage was required after the delivery for some weeks [3].

However, we must consider that the bone surgical saw used in that time was not the twisted cutting saw that we nowadays know as the Gigli's saw. The only flexible saws that were available by then were chainsaws. As we have described, they were similar to the current bicycle chains and had cutting teeth on one side. These saws were used in Heine's *'osteotome'* or similar to the one used by Toison in his craniotomy, as mentioned before.

Gigli's technological contribution consisted of designing a new saw to substitute the existing chainsaws as he considered them complex, not very versatile, easily breakable and, above all, expensive. Accordingly, he contacted a surgical instrument manufacturer from Breslau and ordered a saw made of a toothed steel thread (this later turned into two twisted toothed threads to increase the resistance of the saw) that allowed cutting in all directions. He finally published a preliminary technical note about the correct use and indications of this saw for pubiotomy in 1894. Hence, the lateral pubiotomy with Gigli's saw made of twisted wires (*'drahtsäge'*) rapidly spread within the obstetrics field. Likewise, Gigli recommended using his saw to cut any bone except from the cranial bone.

Three years later, Alfred Obalinski (1843–1898), from Krakow, published an article in *Centralblatt für Chirurgie* in 1897. The article highlighted the potential benefits of the Gigli's saw in cranial resection surgeries. Gigli, who had business acumen and was an innovative person, embraced soon the idea and adapted his saw to the cranial opening in studies carried out with corpses. He particularly designed and improved systems that allowed to introduce safely the saw between the bone and the dura mater without harming it. Gigli also published his technique in *Centralblatt für Chirurgie* just a few months later. The legacy of Leonardo Gigli was his twisted-wire saw and its preeminent use in cranial surgery. Its use in lateral pubiotomy, the intervention for which it was invented, has been forgotten. Once the conceptual problem of the twisted saw that cut in all angles and the need for safe handlers and bolts were solved, there was a subsequent development of the surgical industry that took place immediately and a continuous improvement process concerning all these aspects started.

As it was stated, the Gigli's saw substituted other systems when it came to making cranial openings. It was particularly supported by Harvey Cushing, who imposed his opinions based on either his undeniable authority in neurosurgery during the first half of the twentieth century or indisputable technical aspects. Such aspects included, among others, ease of use, low cost, safety concerning the dura mater and the brain when cutting the bone (as it was done from inside-outwards), speed, generating not much vibration, heat and detritus and lack of more efficient alternative options.

In order to revive the technique of the osteoplastic craniotomy of that time with the Gigli's saw we are going to focus on George Marion (1869–1960), who already described it in detail in his book *'Chirurgie du Système Nerveux'* in 1903 [4]. Marion was a French surgeon who was particularly interested in urology and who operated president Trujillo from the Dominican Republic due to a prostate cancer in 1935. For this reason, he was honoured by the president and a military hospital of the island was named after him. It is remarkable that his works about surgery of the nervous system (in which he included the skull, encephalon, rachis and spinal cord and nerves) are clear and concise. We use it as an example of the accurate description of the technique just as it was done at its early stages. He pointed out that there are two types of cranial opening, the '*ablation d'une rondelle osseuse*' or trepanning and *'par relèvement d'un lambeau osseux'*, which takes place in an intervention that should be called *'craniectomie à lambeau'* or more precisely *'cra-*

niotomie'. He stated categorically that *'Des deux méthodes: trépanation, craniectomie, la dernière est à tous points de vue supérieure'* and he ventured to say that the best system to carry out the craniectomy was the electric saw. However, as installing the motors involved many difficulties the best alternative choice was the Gigli's saw. Marion listed the instruments required to carry out a craniotomy, which are the following: scalpel, scissors, toothed forceps, Kocher's forceps, Reverdin's needle, *'écarteurs'*, Doyen's trephine onto which drillers and burrs were mounted, Gigli's saws and a special guide for it.

The steps of the technique of craniotomy with a Gigli's saw are the following as described by Marion (Fig. 29.2). A horseshoe-shaped incision with the base on the lower part is marked on the skin. It must be placed and done according to the cranioencephalic topography information. The soft tissues are cut until reaching the bone. The bleeding is controlled by means of the haemostatic forceps. The soft tissues along the whole incision are separated showing about 2 cm of bone. The holes along the cut are made using a driller with a triangular tip at first and a spherical burr afterwards, making sure that the dura mater is not harmed. The holes must have a diameter of 12–15 mm so that the Gigli's saw can be introduced. First, a grooved probe that is slightly bent on one edge (this instrument was manufactured expressly for Marion for this purpose) is passed from one hole to another one between the bone and the dura mater. While this probe is kept in that position the Gigli's saw is slid between the probe and the bone. The edges of the saw are introduced in their handles and the bone is cut. The cut of the bone must be slightly bevelled. The base or pedicle of the bone flap can also be completely or partially cut with the saw. A partial cut makes it easier to break it by levering it. Once the intracranial procedure is completed, the bone is replaced by placing the holes and unevenness of the bone facing each other or resecting them with the gouge forceps to achieve a perfect coaptation. To place a drain, it is recommended to make a hole with a driller in the centre of the bone flap across which the drain can pass. In case decompression is recommended in this surgery the bone is removed from the soft tissues. The scalp is closed in a sole plane.

a

Fig. 29.2 Surgical technique of the different types of craniotomy by George Marion. (**a**) Osteoplastic craniotomy showing the bone cut with the Doyen's handsaw (*left*), Dalgren's claw (*center*), and chisel and hammer (*right*). (**b**) Shows the steps of the technique of a trephination and its enlargement using the Farabeuf's forceps. The bone disc is removed using a tirefond. (**c**) Shows the steps of the technique of osteoplastic craniotomy with Gigli's saw. (**d**) Shows a complex osteoplastic craniotomy with a supra- and infratentorial flap obtained with the Gigli's saw, which extends to the suboccipital portion with the bone removed by a gouge clamp (Marion G. Chirurgie du Système Nerveux. Paris: G. Steinheil; [4])

b

Fig. 29.2 (continued)

c

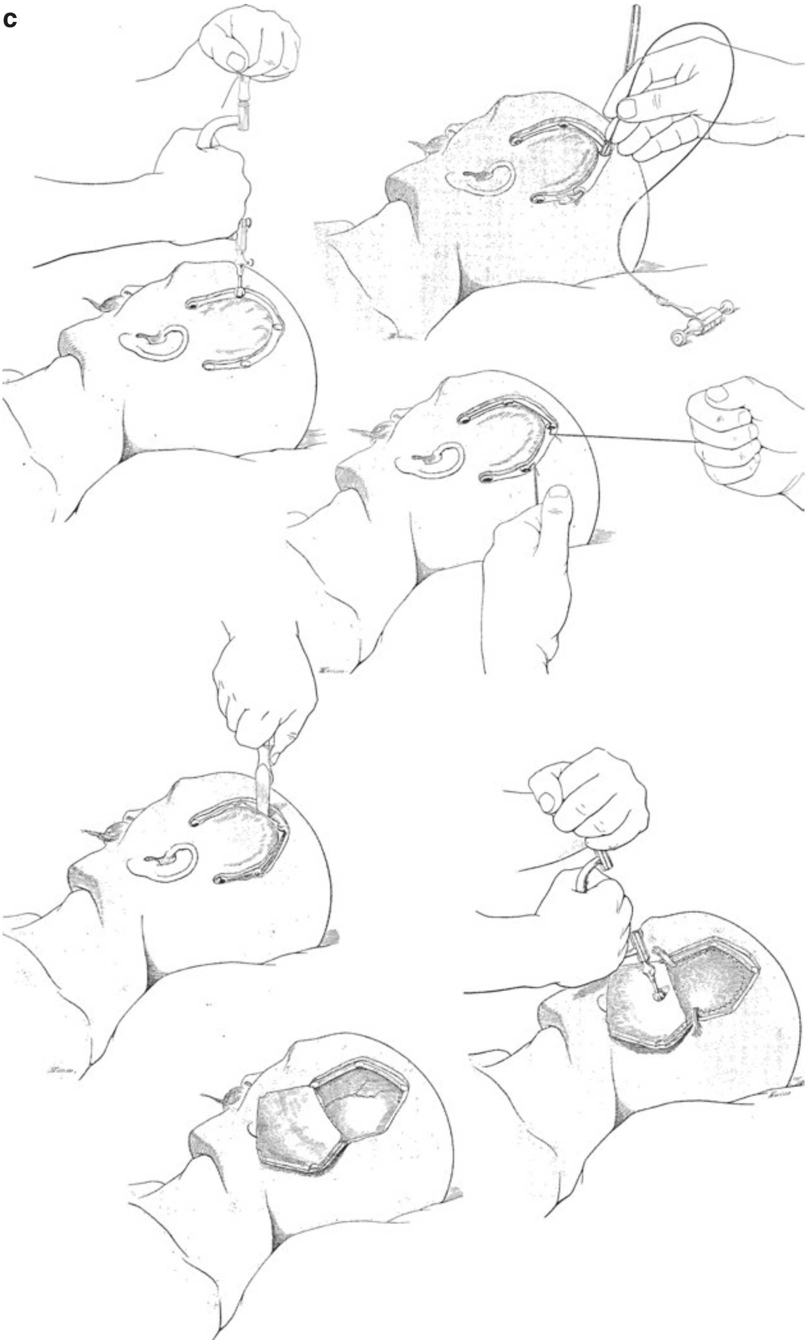

Fig. 29.2 (continued)

d

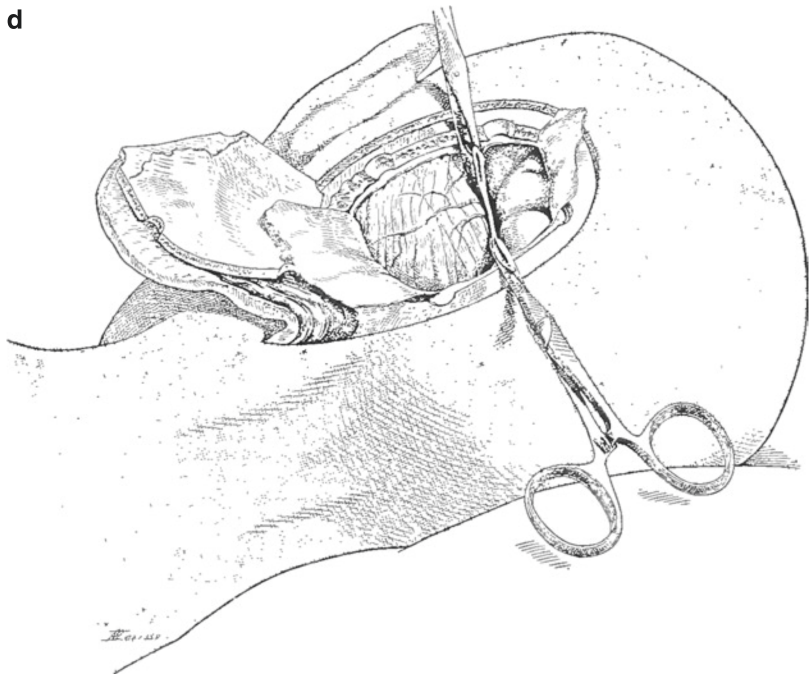

Fig. 29.2 (continued)

A few years later, Thierry de Martel (1875–1940) stated in his book *'Blessures du crâne et du cerveau: formes cliniques, traitement médico-chirurgical'*, which was published in [5] with Ch. Chatelin that the craniectomy is only effective when it is carried out quickly, without shaking the patient's brain or making it vibrate and without harming the brain or even the dura mater. He rejected to use the mallet and the chisel to avoid shaking the patient's head. To avoid harming the dura mater the best option is to cut from inside-outwards with the Gigli's saw. The speed can be achieved by quickly drilling the skull and passing the saw from one hole to another one. This procedure must be done safely, using the appropriate instruments. De Martel invented a series of instruments for craniotomy, which M. Collin manufactured. These instruments were used as a demonstration of the speed, ease of use and safety, like the T haemostatic forceps for the flap, a cranial driller with a stop and a braking system, an instrument to lift the osseous flap once it had been fractured on its base and a guide for the Gigli's saws. Martel's guide for the Gigli's saw, which works either as a probe or as a protecting system, consists of a sheet with a length of 25 cm and a width of 8 mm. It is made of steel and it is completely elastic and slightly warped but not malleable. One of its edges or ends is a bit enlarged to separate the dura mater from the bone. 10 cm far from this edge, in the concave part of the instrument, there is a hook pointing towards the enlarged end. The edge of the guide is introduced through one hole and the surgeon pulls the guide from the second hole. In that moment the handle of the Gigli's saw is hooked and it is slid until it reaches the second hole and emerges from it. Now the handle is unfastened and both edges of the saw are connected to the grippers (handles) to cut the bone. An assistant tightens the guide between the holes so that the saw is not loosened up. The model of this guide was kept among the neurosurgical instrument sets for decades.

As we have already mentioned, one of the greatest supporters of this osteoplastic craniotomy with pedicle flap was Harvey Cushing (1869–1939). Cushing is also considered as the surgeon who defined the neurosurgery as a modern specialty and who laid the foundations for current neurosurgery. He integrated the biological and clinical knowledge and the treatment of gliomas, meningiomas, acoustic neuroma and pituitary tumours. From a surgical point of view, we can state that he was the best specialist among neurosurgeons and he was considered the most important neurosurgeon of the first half of the twentieth century. His most important contribution to the technique of craniotomy was probably his obsessive care for each detail concerning the cranial opening and closure. For example, he recommended a careful closure of the dura mater and the galea aponeurotica, avoiding drains.

Cushing's prestige in the neurosurgical field was the reason why his statements were quickly supported, without criticism. We have already mentioned that his opposition to motors and saws with an outside-inward cutting system caused a widespread use of the trepans with a brace handle to make the holes and the Gigli's saw to cut the bone. One of the most representative images of the osteoplastic craniotomy is an original drawing made by Harvey Cushing. It was included in the chapter *'Intracranial tumours'*, which he wrote in volume 2 of the book '*Surgery: Its Principles and Practice'*. His mentor William Williams Keen (1837–1932) was the editor of this book, which was published in [6]. It shows a left frontal-temporal craniotomy to treat a frontal wound caused by a firearm. It is worth commenting, as an anecdote, that the faces of the patients that appear in that chapter resemble a lot to his mentors' doctors Osler and Halsted.

As many other surgeons of that time, he still carried out a cranial opening with bone resection by means of gouge forceps in some approaches, particularly those concerning the base of the skull and the posterior fossa. Concerning the cerebellopontine angle tumours, Cushing preferred a bilateral suboccipital approach by craniectomy. It was carried out across a T-shaped incision by resecting the bone with gouge forceps after making a burr hole on each side of the occipital bone. He showed his opposition to both unilateral and medial approaches to the cerebellopontine angle by osteoplastic flap according to Krause's technique in the book *'Tumors of the nervus acusticus and the syndrome of the cerebellopontile angle'*, which was published in 1917 [7]. Cushing was also one of the supporters of the decompressive craniectomies, particularly those carried out at a subtemporal level either on one or on both sides in order to treat inoperable tumours. He also carried them out with gouge forceps by enlarging an initial burr hole.

We have only found evidence of some criticism to Cushing's ideas and leadership in the following words from an eminent North American surgeon who worked in Canada, Wilder Penfield (1891–1976), who commented Cushing's technical heritage in 1946. He flattered him at first *('Harvey Cushing was the first superlative technician among neurosurgeons'*) but ended up with some veiled criticism concerning his methods, as he considered them too classical (*'This set of technical procedures might be called the classical pattern. When one detail is altered many others must be changed. But to continue to adhere to it would be to miss the opportunity for advance'*) [8].

Whatever the case, the cranial opening based on small cranial holes made with a drill and connected with a Gigli's saw became the universal technique of cranial opening for osteoplastic craniotomies until the 80s. As time went by, some additional improvements were introduced gradually after overcoming many difficulties in the surgical practice of cranial approaches, which were becoming increasingly widespread.

The development of these contributions can be found in the surgical technique books published or followed by each neurosurgical school or neurosurgeon. In our case, our early guide text along our Residency period was the book *'Operative Neurosurgery'* written by Ludwig G. Kempe (1915–2012) in 1968. It was passionately followed in Spain thanks to the Spanish translation that Adolfo Ley Gracia carried out in 1972 under the title *'Técnicas Neuroquirúrgicas'* [9]. This clear and concise book taught the author the techniques on basic approach to the skull during his training period. Kempe was born in Germany. He studied Medicine in Switzerland but soon he moved to the United States, where he developed his professional career as a neurosurgeon of the Armed Forces. The book is organised in different chapters that include the relevant pathology of each topographical area and its approach. The text is short, concise and direct and includes simple instructions and practices. The beautiful prints, which were drawn by Kempe himself, include the position of the patient on the operating table, the surgical vision of the head and the lesion just like the surgeon could see it with his eyes, the surgical anatomy of the pathology and the approach and resection technique (in no more than two or three drawings). The prints have light and bright colours. The frontal-temporal craniotomy is described in detail in Chap. 1. It is a wonderful documentary example of the *'state of the art'* of the technique of osteoplastic craniotomy during its greatest splendour in the second half of the twentieth century. The pericranium flap is lifted on its own as a first layer, and many Dandy's forceps are used for the haemostasis of the pericranium. The burr holes are made with an electric driller but the Gigli's saw is used to cut the bone between them. The base of the osseous flap is fractured by lifting it. This can be done after weakening it with the bites of the gouge forceps. The osseous muscular flap is kept away from the operative field, wrapped in a damp pad that is fixed to the drapes. Later editions include new options, such as Michel or Raney clips for the haemostasis of the cutaneous flap instead of Dandy's forceps, as well as the osseous opening with a vertical-cutting electric saw instead of Gigli's saw.

The fact that, although new indications were introduced and the neurosurgical techniques were improved and refined, the habit of leaving the osseous flap connected to the musculocutaneous flap was maintained for decades is particularly interesting (Fig. 29.3). Afterwards, as described above, it was only connected to the muscle flap. This nearly obsessive idea of keeping the bone flap attached to the pericranial soft tissues was based on the old belief that this granted the survival of the osseous flap and avoided its late necrosis. It was not until late in the twentieth century when they started adopting the practice of separating the osseous fragment from the soft-tissue flap and leaving it away from the surgical field temporarily, on the instrument table so that it could be replaced at the end of the procedure. This was the beginning of the age of the osteoplastic craniotomy with free bone flap. During these same years the procedures of making burr holes and cutting the bone with manual instruments were massively substituted by procedures with mechanical devices and instruments that involved electric or pneumatic motors.

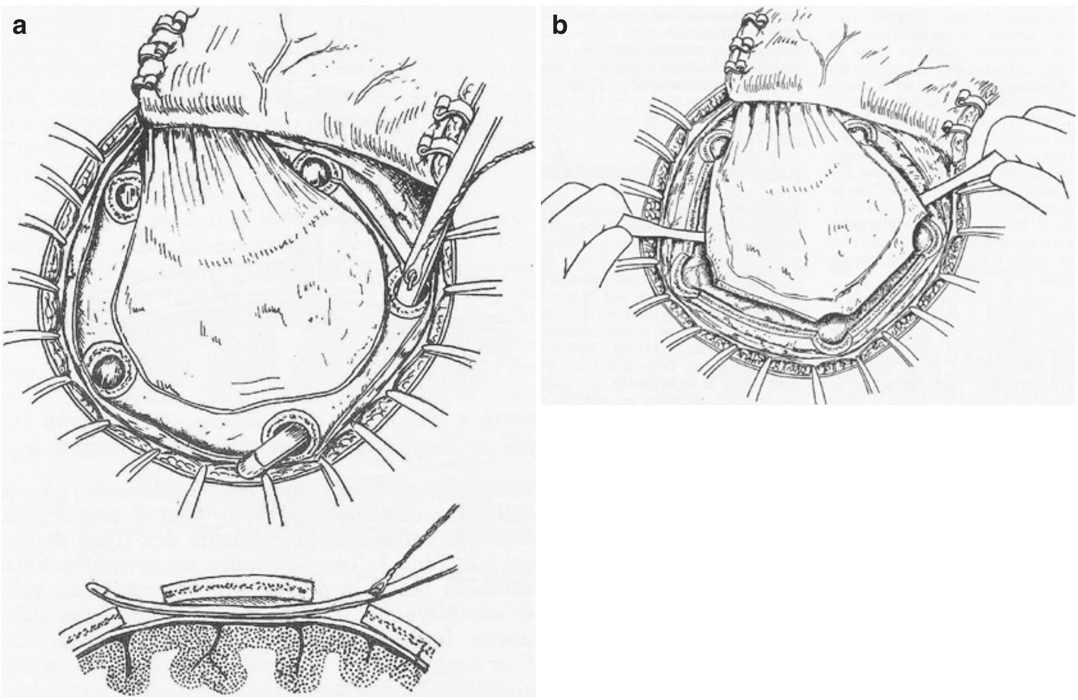

Fig. 29.3 Figures presenting the steps of a pedicle craniotomy with Gigli's saw. (**a**) Shows the pass of the Gigli's saw protector under the bone between two consecutive burr holes. The saw is attached to the guide. (**b**) Shows the elevation of the flap using two elevators. The bone between the two basal burr holes under the temporal muscle must be fractured. (**c**) The bone flap attached to the muscle has been elevated. Dandy forceps are placed on the galea around the incision. In the skin flap several metallic staples are also placed (Karaguiosov L. Técnica neuroquirúrgica. La Habana: Editorial Científico-Técnica; [10])

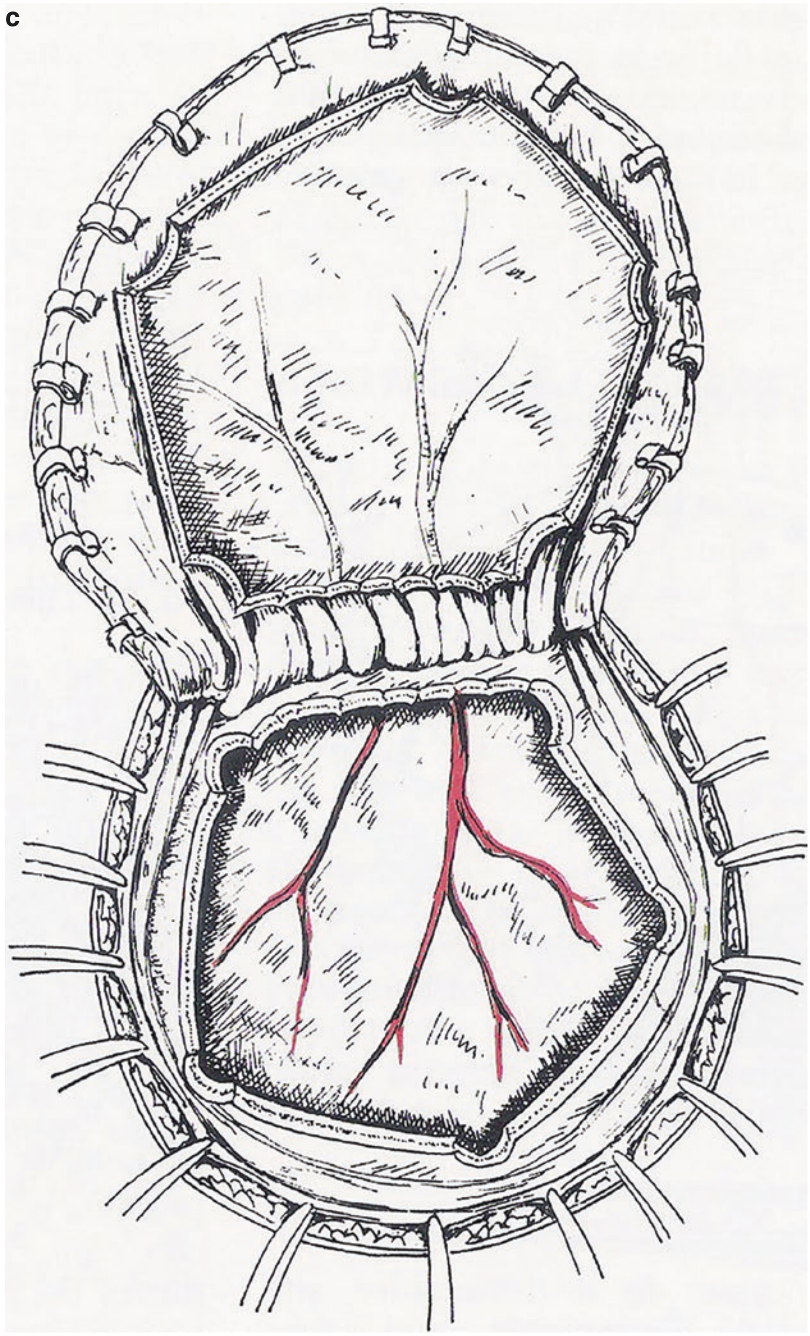

Fig. 29.3 (continued)

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30 Late Development: Powered Osteoplastic Craniotomy

The alternative to the manual opening described in many ways was the electric motors. It is curious how fast electric motors specifically designed for craniotomy were invented as we must consider that electricity had just being invented in that time. It was not just a matter of modernity. The truth is that manual craniotomy, just like any other described, was a terrible procedure for the patient, the surgeon and their assistants. However, motors and instruments designed to be used with electric power had a short success and a limited scope. It is true that primitive electric motors were expensive, heavy, dangerous and not very versatile. But the reason for failing is due to many other aspects that we will analyse.

Some instruments with mechanic circular cutting and manually triggered by crank systems were developed in the nineteenth century before electricity. They were included in the medical texts and catalogues of instruments of that time. Many clever developments appeared during those years, always following the progress of the dental surgery motors. The first modern reference concerning the use of motors in neurosurgery was Sir Victor Alexander Haden Horsley (1857–1916), who used Bonwill's manual circular saw in 1887. He did not consider it useful and dismissed it soon. After many frustrated attempts, M.H. Cryer invented a vertical-cutting spiral electric saw with dura mater protection, with coupling pieces for burrs and trephines in 1893. He recommended continuous irrigation. This device was surprisingly not accepted in spite of having a design that was almost similar to modern motors of the second half of the last century. Doyen's amazing electric motor, along with its instruments and accessories that we will later describe, was also forgotten.

It is curious that none of these systems was successful due to many factors, for example the excessive warming, vibration, waste production, inefficiency, accidents on patients and surgeons, motor failures or availability. In addition, as we have mentioned, these attempts to motorise the instruments had to face criticism from the leading figures of cranial surgery of that time. This was particularly obvious in the case of Harvey Cushing (1869–1939), who was radically against motors. He argued that they produced excessive vibration for the brain and were dangerous as the saws that were available cut the bone from outside-inward. The simple and efficient design of the Gigli's saw ended up succeeding in this technological competition.

From the beginning, there were many attempts to carry out craniotomies using mechanical systems. These systems were initially manual but soon they were powered by electric motors. These first attempts of mechanic and electric motorisation were generally a consequence of applying the new technological advances to neurosurgery. These developments had been previously introduced in the field of dentistry to

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motorise it. All these attempts started failing one after another after a pretty short life. The reasons for failing have been previously mentioned.

We have described the motors and instruments for electric craniotomy invented by the French surgeon Eugène Louis Doyen (1859–1916) [1]. Another French surgeon, Thierry de Martel (1875–1940), presented a motor-driven trephine in 1908 [2]. It also had an autobraking system that stopped the spinning movement as soon as the skull had been drilled. De Martel made demonstrations in medical conferences by using a dry skull with a blown-up balloon inside that emulated a dura mater. After drilling the skull, the balloon was intact. It was so easy to use that, in his words, *'ce trépan peu manié même par un imbécile'*. The motor of Martel's mechanical instrument system for craniotomy, just like the one invented by Doyen, could be powered by electricity or, even better, by operating pedals. De Martel described it as follows: *'un moteur de mon invention mis en mouvement par un aide qui peut être une femme ou un enfant. Je préfère ce dernier moteur parce qu'il ne se détraque pas et qu'il peut être utilisé n'importe où ...'*. The motor shaft was coupled to its cranial driller and to a vertical-cutting saw, which also had a dura mater protection system similar to the current ones. He boasted that '*Toute l'opération demande de deux à trois minutes et est admirablement supportée par le blessé non endormi. Il est à remarquer que l'opéré éveillé ne se plaint pas des vibrations de l'instrument, ceci pour répondre à l'objection que certains chirurgiens font à cette technique'*. His equipment had a relative success in Europe. However, just like many other electrical drilling methods, it never became popular in the United States as it opposed to Cushing's ideas, based on the likely danger of the effect of the excessive vibrations caused by the motor on the brain.

Water (and later air) turbines were subsequently reintroduced and eventually prevailed in order to drive cranial drilling instruments [3]. The physicians Forest C. Barber and Ronald Smith, the latter being a neurosurgeon, developed the first pneumatic neurosurgical motor (Turbobit) in S&B Tools in Fort Worth (Texas, USA) in 1962. It was pretty successful as it allowed carrying out a craniotomy in 2–3 min, they said. In that time the procedure used to take far more time. This primitive motor was improved by Barber from the company Midas Rex, also placed in Fort Worth. On the other hand, Robert Hall presented the Hall Air Drill in the orthopaedic field in 1963. It was modified in 1969 so that it could be used in neurosurgery. The impact of this technology was so great that Hall was nominated for the Nobel Prize due to the development of these products. These initial models contributed to the consolidation of the use of compressed air-driven motors in neurosurgery. They allowed to carry out any type of cranial drilling, either burr or trephine holes and cutting the bone between the holes to complete the craniotomy.

The first modern pneumatic craniotome was developed by John H. Bent, a mechanical engineer who owned Standard Pneumatic Motor Company, which was outsourced by Hall Air Instruments of Santa Barbara (California, USA), which in turn was purchased later by 3M. The craniotome had a body with the motor linked to a rubber tube connected to the compressed air source. On the distal part the skull driller or perforator that allowed to make the holes could be replaced by a vertical-cutting saw. The perforator had different diameters and also had a braking system to avoid damaging the dura mater when the drill was completed. The driller was used with a rpm reductor for the motor, where the standard output speed is reduced to the required speed for a particular attachment or piece. The saw made vertical cuts and had a dura mater protection system. It allowed the motor to spin at a greater number of revolutions. The first craniotomes only allowed the saw to cut in just one direction. For this reason, once the initial cut was made the saw followed a straight line from one hole to another one. This forced neurosurgeons to make many burr holes to achieve the craniotomy they wanted, which always had a polygonal shape. Hence, Codman developed a technical modification of the drilling depth consisting of a vertical saw with a rotating head (Codman Rotatable Duraguard). This allowed making straight and curved cuts conveniently for the first time to achieve the desired osseous flap from just one or two burr holes.

Cutting-edge craniotomes work at high speeds and were derived from the legendary Midas Rex Classic motor, which was presented by Barber in 1980. It served as a model for the development and improvement of other motors manufactured by themselves or by other companies. They are used nowadays in almost all neurosurgery departments. These motors are small and ergonomic and have rpm reductors to make burr holes with perforators and coupling pieces of all types and sizes to use them at high speed with a wide variety of vertical saws and burrs. It is noteworthy to mention that, due to a combination of factors, there has been a change in the propulsion systems of the motors. Nowadays they are mainly electric, such as those developed by B. Braun/Aesculap in Europe, by NKS in Japan and by Medtronic MidasRex or Sinthes Anspach in the United States.

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31 Evolution of Indications of Craniotomy

Modern craniotomy was invented by Wagner in 1889 in order to treat post-traumatic epidural haematomas [1]. However, it was soon noticed that this cranial opening was useful to treat a wide range of intracranial lesions. All intracranial pathologies that are included in the heritage of current neurosurgery have been incorporated gradually to the pool of indications of craniotomies since the beginning of the twentieth century. As these new indications increase, the importance of traumatic injuries within the group of indications of cranial surgery is rapidly declining. We are going to consider different indications (some of them successful and others that failed and were abandoned) in order to give a general outline of these changes.

31.1 Craniotomy for Intracranial Tumours

When the osteoplastic craniotomy was introduced at the end of the nineteenth century, most trepanations were made to treat cranial fractures or their infectious or haemorrhagic complications, as well as the post-traumatic epilepsy. It is interesting to observe how new indications related to intracranial tumours were quickly added to the medical texts as the interest on traumatic injuries and the space set aside for describing them were reduced.

We must remember the epic beginnings of brain tumour surgery by bringing back the words from the surgeons of that time. Henri Duret (1849–1921) expressly wrote in 1905: *'La chirurgie cérébrale des tumeurs est délicate et difficile, mais elle arrivera bientôt à la période des succès fréquents'*, pointing out that brain tumour surgery was by then only 15 years old [2]. Although this was a short period of time, Duret described three consecutive stages. The first stage took place in years 1890–1891 when the first interventions on brain tumours were carried out by trepanations that were enlarged with trephine crowns of a greater diameter and using bone gouge forceps or Farabeuf's trepan-forceps. The second stage started when Wagner's temporary craniotomy was introduced and used. This technique made it possible to forget the previous 'mutilating' interventions which involved a definitive bone resection of the skull. The greatest example thereof in terms of size and sophistication was Doyen's temporary hemicraniectomy. Duret considers that the last stage starts with the French Congress of Surgery of 1903, where they entered a phase in which the technique was improved thanks to the widespread use of the Gigli's saw and the design of craniotomies adapted to the brain topography. The first statistics of indications and results were published by then as well.

As it was expected, the first approaches to the surgical treatment of intracranial tumour lesions were particularly cautious. George Marion

J. M. González-Darder, *Trepanation, Trephining and Craniotomy*,
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(1869–1960) was very prudent concerning the management of intracranial lesions in his book *'Chirurgie du Système Nerveux'*, published in 1903 [3]. He pointed out that as it was impossible to know the type of intracranial lesion and, as they involved a wide variety of clinical and topographical presentations, it was necessary to treat the common symptoms of all of them. Hence, any intracranial process had to be generically considered as an expandable lesion and be treated in a similar way. Marion described it as follows: *'Toute production, … est susceptible d'en augmenter la pression intérieure et de comprimer ou de détruire une partie de la masse encéphalique mérite le nom de tumeur intra-crânienne et se trouve justiciable des considérations thérapeutiques qui vont suivre'*. Among these pathological processes he included exostoses, tumours of the meninges (fibromas, angiomas, sarcomas and endotheliomas, the latter were not mentioned in classical books) and brain tumours (those concerning the brain tissue or encephalomas and gliomas; epithelial metastases or carcinoma or those affecting the connective tissue; tuberculous or syphilitic gummas, cysts and others). Although Marion's surgical experience is limited to six cases, he shows a lot of criticism about those authors who are very enthusiastic with the results. This particular vision of the tumour surgery explains way Marion wrote a long chapter focusing on traumatic injuries, where he considered the treatment of effusions, infections and post-traumatic epilepsy. In this chapter we must highlight the exhaustive description of the localisation and removal techniques concerning projectiles that are lodged inside the skull. These techniques were based on the use of radiographic or radioscopic equipment and a very rudimentary mechanical stereotactic systems that were fixed to the skull and by directed insertion of electromagnetic extractors.

A bit later, Eugène Louis Doyen (1859–1916), who followed a similar conceptual evolution, wrote a long chapter about traumatic cranial injuries in his book *'Traité de thérapeutique chirurgicale et de technique opératoire',* which was published in 1909 [4]. He recommended carrying out a craniotomy when there were probable signs of intracranial effusion and brain compression, as well as when treating depressed fractures. He states that the *'craniectomie pratiqué par un chirurgien habile est inoffensive'* and that even if no effusion is found and the patient is going to die due to the concussion or a cerebral contusion the intervention should not be criticised as it is the only chance to heal. He recommends making exploratory burr holes in the area where the effusion is suspected, particularly on the side where the pupil is more dilated, and the use of radiography to find out foreign bodies. He also recommends craniotomies for inflammatory lesions and infections such as abscesses, microcephaly and Jacksonian and essential epilepsy. As for brain tumours, he has a more cautious point of view. He starts saying that the intervention is only successful in case of well-localised and benign tumours, although the type of tumour can only be determined after the histological analysis after surgery. He includes a wide range of pathologies among brain tumours, such as tuberculomas, gummas, gliomas, sarcomas, endotheliomas and metastases. He recommends large temporary craniotomies, as large as hemicraniectomy.

Fedor Krause (1857–1937), only included a small chapter of barely ten pages focusing on head wounds and fractures in his spectacular book '*Chirurgie des Gehirns und Rückenmarks*', which was published in 1907. This contrasts the chapter on surgery of brain tumours which extends over 120 pages [5]. He described the intracranial hypertension syndrome and then he studied separately the clinical features and peculiarities of the approach of hemispheric tumours of frontal, parietal, temporal and occipital lobes and those in central region, lateral ventricles, pituitary, posterior fossa and cerebellopontine angle, including many demonstrative clinical cases. He briefly mentioned decompressive craniectomies and reviewed different puncture techniques. To remove the tumours, he developed an original suction method using an ampoule. He considered that this method was better than removing the tumour with the finger that was generally done in that time. Krause systematised intracranial tumours according to their topography, describing thus their clinical manifestations and surgical treatment. Other texts from those years include long chapters aimed at describing neurological syndromes of the lobes and in other locations caused by brain tumours and diagnosing the type of tumour.

Authors used to gather in their books the cases published by other authors in books and papers and presented in conferences during the first decades of the century. Henri Duret (1849–1921) gathers a total amount of 400 cases in his work *'Tumeurs de l'encéphale. Manifestations et Chirurgie'* [2]. It includes not only neoplasms but also a great deal of tuberculomas, syphilomas and hydatid cysts. According to the author, these lesions are authentic tumours as they require opening the skull and intracranial procedures. A quarter of the lesions had an unknown origin and cannot be determined. Rapid deaths after surgery were caused in 14% of the cases by the shock; in 10 cases they were due to the bleeding and in other 10 cases due to an early hyperthermia. Around a 5% of the patients died of meningoencephalitis. The total mortality during the first month of the post-operative period was 36.25% among those who underwent surgery. The amount of recoveries and significant clinical improvements exceeded half of the cases. A total of 41 cases with recurrence were reported.

Harvey Cushing (1869–1939) was probably the neurosurgeon who clearly isolated and described the most frequent types of tumours within the neurosurgical practice of that time. He classified them according to their nature and then he explained their origin, histopathology, topography and characteristic syndromes, as well as the most suitable neurosurgical treatment. All this was the result after a huge, exhaustive and brilliant personal work. He addressed cranial traumas in his first publications, as he had to treat them when he was serving in Europe during World War I. However, he later focused mainly on brain tumour surgery. Cushing laid the foundations for the knowledge and treatment of these lesions, a topic which was later developed and researched [6]. Cushing classified tumours in four main types; each of them was the subject matter of one of his seminal books: brain gliomas (*'A classification of the tumours of the glioma group on a histogenetic basis, with a correlated study of prognosis'*, 1926, by Percival Bailey and Harvey Cushing); meningiomas (*'Meningiomas. Their classification, regional behaviour, life history, and surgical end results'*, 1938, with contributions by Louise Eisenhardt); pituitary tumours (*'The Pituitary Body and its Disorders. Clinical states produced by disorders of the hypophysis cerebri'*, 1912); and, finally, acoustic neuromas (*'Tumours of the Nervus Acusticus and the syndrome of the cerebellopontile angle'*, 1917). Cushing also reviewed the encephalic vascular pathology (*'Blood Vessel Tumours of the Brain'*, 1928). However, the approach to the vascular pathology was done from a similar point of view to the one adopted with tumour lesions, which was completely different to what would be contemplated later. As many other authors from that time, he did not show much interest in brain metastases.

This way, the basic types of tumours in neurosurgery and their clinical and surgical management were defined before the half of the past century and thanks to Harvey Cushing's works. Post-operative mortality of brain tumours had been very high until then. Only 5–10% of brain tumours that had been clinically diagnosed were considered operable and the mean post-operative mortality was between 30% and 50% according to the series (even greater if the posterior fossa tumours were assessed separately) during the first decades of the past century. A significant percentage of suspected lesions was not found in spite of the craniotomy. Cushing reduced the mortality thanks to an excellent surgical technique, the intraoperative monitoring of arterial pressure and heart rate, the adoption of new haemostasis measures or the improvement of the position of the patients. However, what was particularly useful was his use of palliative surgery such as cranial decompressions or subtotal tumour resections.

As for the technique of craniotomy, Cushing made a pedicle osteoplastic flap with manual burr holes and a Gigli's saw to approach hemispheric lesions, using the temporal muscle as the base of the osseous-muscular-cutaneous flap. The first osteoplastic craniotomies of the posterior fossa, both for the cerebellum and the cerebellopontine angle, were made with large incisions with the shape of a horseshoe and by detaching all of the nuchal muscles from the occipital bone. Cushing even used uncomfortable constructions made of plaster to immobilise the cervical region and promote cicatrisation. The resection of the suboccipital bone became less traumatic later by means of an incision on the middle line, which could be T-shaped or linear. After removing the periosteum from the bone, a burr hole was made on each side, which was enlarged manually with the gouge forceps. Resecting the posterior arch of the atlas was a normal procedure. It allowed to achieve an adequate decompression of the foramen magnum that was systematically occupied by the herniation of the cerebellar tonsils. The occipital cranial opening was generally left open and protected with a hermetic and watertight closure of the muscular soft tissues, which have a greater thickness in this area.

31.2 Craniotomy for Cerebral Aneurysms

Although intracranial aneurysms were known thanks to anatomical studies they did not involve any drawback for neurosurgeons until the Portuguese Medicine Nobel Prize laureate, Egas Moniz (1874–1955), introduced the cerebral arteriography in 1927, which allowed an imaging diagnosis in living patients thereof. Charles Putnan Symonds (1890–1978) was the first neurologist who recognised their importance concerning the subarachnoid haemorrhage in a paper published in 1924. We must point out that Harvey Cushing (1869–1939) himself commented this work and defined these lesions as *'lesions having … remote surgical bearings'* showing a total and surprising lack of vision of the future and just admitting their importance in order to differentiate them from brain tumours. The first attempt of aneurysm obliteration was carried out by Norman Dott (1897–1973) using a piece of muscle. It has been documented that Walter Dandy (1886–1946) was the first neurosurgeon who carried out a brain aneurysm exclusion by placing a silver clip on its neck. It was an aneurysm that affected the posterior communicating artery and the surgery took place on the 23rd of March of 1937. We must mention Cushing again, as Dandy used the silver clip that was invented by Cushing in 1911 and which he had never used. It had been designed to be placed in delicate vessels or in those with a poor or difficult access for ligation.

Leaving apart these historical considerations, cerebral aneurysm management did not involve any modification in the technique of craniotomy as the procedure of clipping used the same craniotomies as in tumour surgery. Brain aneurysmal vascular pathologies and those pathologies concerning arteriovenous malformations were consolidated within the field of neurosurgery when M. Gazi Yasargil (1925–) introduced the operating microscope to treat them [7, 8]. Yasargil, a Turkish physician trained in Switzerland who is considered the most important neurosurgeon of the second half of the twentieth century, systematised the pterional craniotomy for the treatment of aneurysms. He named it 'interfascial pterional craniotomy' or 'frontotemporal sphenoidal craniotomy' and stated that it was useful for anterior circulation aneurysms and distal basilar artery aneurysms, as well as for tumours in orbital, retro-orbital, sellar, parasellar, chiasmatic, subfrontal, retro-clival and pre-pontine regions. He highlighted that the key points of the technique are the position of the head, the adequate resection of the bone on the base of the skull, the evacuation of cerebrospinal fluid from the basal cisterns and the systematic dissection of the subarachnoid space and the basal cisterns. The term 'interfascial' refers to the fact that the dissection of soft tissues is done between the two layers of the superficial fascia of the temporal muscle. This procedure aims to protect the superior branches of the facial nerve to avoid the post-operative palsy of the muscles that are innervated by them. The separation of the temporal muscle from the bone must be done by keeping intact the deep temporal fascia, as this allows maintaining the innervation and vascularisation of the muscle and avoids post-operative atrophy and fibrosis. The cranial opening is achieved by making two or more burr holes with a drill and cutting the bone with the Gigli's saw. This creates a free flap that is replaced once the surgery is over. The bone in the lesser wing of the sphenoid bone is milled outside the dura mater to avoid brain retraction. Finally, we must highlight the term ‘trans-sylvian’ because the approach, during its intradural stage, is based on a delicate and exhaustive opening and dissection of the sylvian fissure. Hence, this approach is more often called pterional-trans-sylvian approach.

Although Yasargil laid the foundations for the approach to anterior circulation brain aneurysms we can consider the Canadian neurosurgeon Charles George Drake (1920–1998) as the pioneer concerning the treatment of posterior circulation aneurysms through suboccipital or subtemporal craniotomy. Many other neurosurgeons continued developing microsurgery for vascular lesions. However, we would like to highlight again that this did not involve any significant contribution or modification to the technique of craniotomy.

31.3 Craniotomy for the Resection of the Gasserian Ganglion

The essential trigeminal neuralgia is a devastating condition for the patient that nowadays has an excellent surgical and pharmaceutical solution. However, it has not always been this way. The surgical treatment forced surgeons to develop complex approaches and very specific craniotomies that were abruptly and definitively abandoned as the physiopathological knowledge of the illness increased. We have developed this section as an example of the surgeons’ fruitless battle against the condition as their effort was based on wrong physiopathological ideas.

The aim of the surgical procedures developed at the end of the nineteenth century and the beginning of the twentieth century for the treatment of the trigeminal neuralgia was cutting all sensory afferent fibres of the cutaneous region of the trigeminal nerve that lead to the nervous central system. This was only carried out in those cases of a refractory neuralgia to a neurectomy of the peripheral branches of the trigeminal nerve, which was the most frequent surgical procedure in that time. The anatomic regions that were chosen as a target were the trigeminal nerve root, the semilunar Gasserian ganglion and the origin of the three main peripheral branches. All of these anatomical structures are located in the middle cranial fossa. In order to do so, a great amount of interventions was massively developed almost at the same time by famous surgeons, such as Victor Alexander Haden Horsley (1857–1916) and Frank Hartley (1856–1913) in the United States, Eugène Louis Doyen (1859–1916) in France and Fedor Krause (1857–1937) in Germany.

These authors published their observations and technical proposals almost at the same time but separately. It is hard to accurately determine the intervention carried out in some cases due to the difficulties that authors faced to recognise the neurological structures that were cut or removed. The reason for this was that the approaches were small, the bleeding hid the structures or there were anatomical mistakes or ignorance of the complex anatomy of the region. This confusion makes it difficult to identify the original author of each intervention or description. In any case, regardless of the real or potential intervention on the nerve, the approach was done by a temporal craniotomy that was specifically designed for such purpose by each author.

Horsley carried out the approach in 1890 by resecting the zygoma (a procedure that he would consider unnecessary later), dividing the temporal muscle and making a cranial opening with a diameter of 3–4 cm with a trephine and enlarging it with gouge forceps. On the contrary, Krause carried out the approach by an osteoplastic temporal pedicle flap made with two trepans joined together with Dahlgren rongeur forceps, without resecting the zygomatic arch. The craniotomy with gouge forceps can be done through a vertical linear incision whereas the pedicle flap requires a larger incision with the shape of a horseshoe. Doyen, in turn, prefers a vertical incision and resecting the zygomatic arch. He drills on the spheno-squamous suture and enlarges the cranial opening with gouge forceps until reaching the sphenoidal crest. He goes on resecting the horizontal section of the greater wing of the sphenoid bone until reaching the foramen ovale, where he identifies the third branch of the trigeminal nerve that serves as an anatomical reference to continue until completing the ganglionectomy.

These interventions were particularly mutilating for the patient, as they caused a severe atrophy of the temporal and masseter muscles after cutting the motor root or third branch of the trigeminal nerve. They frequently involved the loss of the eye due to a keratitis caused by the sensory denervation of the conjunctiva and the cornea, which depend on the first branch of the trigeminal nerve. The surgical complications were numerous and devastating. They were caused by an arterial haemorrhage from the middle meningeal artery or by venous haemorrhage from the cavernous sinus, as well as by inadvertently cutting the superior cerebellar artery during the rhizotomy, damaging the facial nerve at the geniculate ganglion level or other cranial nerves in the cavernous sinus, a cavernous sinus thrombosis, intraoperative or post-operative shock or infection. The situation only improved from 1910 to 1915 after improving the technique and carrying out partial rhizotomies more frequently.

Meanwhile some authors recommend and try to carry out a trigeminal rhizotomy through the posterior fossa. Doyen reported an attempt with an endoscope inserted through a cranial opening of 20 mm of diameter carried out on the asterion in 1917. However, Walter Dandy (1886–1946) was considered the inventor or trigeminal rhizotomy by means of a posterior fossa approach. The advantages associated with this pathway were the speed and the simplicity, as well as the selective sectioning of the sensory fibres that allowed healing and avoided a significant loss of the sensitivity and thus a lower risk of keratitis. It also allowed to preserve motor fibres and avoided so many damages to the facial nerve and other cranial nerves.

Ludwig G. Kempe (1915–2012) included in his book *'Operative Neurosurgery',* which was published in 1968, either the classical temporal or the suboccipital approaches in a very detailed way [9]. This means that both approaches coexisted for many years, during the pre-microsurgical period.

Dandy reported in 1932 that in over 500 cases of rhizotomy in the cerebellopontine angle, he found that 10% of the cases showed a compression of the trigeminal root due to tumours or aneurysms but *'in almost every additional case, the nerve is grooved or bent by a loop of the anterior inferior cerebellar artery* (superior cerebellar artery?). *This I believe is the cause of tic douloureux'*. In spite of this remark, Dandy never gave importance to this neurovascular relationship as a cause of the neuralgia. Peter J. Jannetta (1932–2016) was the first who applied the operating microscope to the trigeminal rhizotomy surgery in the cerebellopontine angle. Jannetta confirmed Dandy's observation about microvascular compression of the trigeminal root and postulated the simple decompression thereof from these vascular elements as a physiopathological treatment of the trigeminal neuralgia in 1967. From this moment on the rhizotomy collapsed due to the retrosigmoid craniotomy or the middle fossa craniotomy. Nowadays the microvascular decompression of the trigeminal root in the posterior fossa through a retrosigmoid craniotomy is the surgical treatment of choice for the essential trigeminal neuralgia.

31.4 Decompressive Craniectomy

In spite of the large cranial opening provided by the craniotomy the tumour could not be found or was inoperable in a pretty significant number of patients for decades. In these cases, the recommendation was leaving the cranial opening open and making a careful closure of the soft tissues in order to try to control the endocranial hypertension to achieve, at least, a palliative symptomatic treatment. Fedor Krause (1857–1937) recommended enlarging the craniotomy by making a resection of 1–2 cm of bone around it with gouge forceps and keeping the osseous flap in its original position. This way an area of dura mater was left intact around the margins of the cranial opening and the herniation of the brain lifted the osseous sheet that protected the suture line of soft tissues [5].

Harvey Cushing (1869–1939) contributed to this field by recommending a mere palliative decompression when there were no chances to remove the tumour (Horrax 1944). In order to do so, he suggested carrying out a decompression by a cranial opening on the lower temporal region for supratentorial tumours and on the suboccipital region for infratentorial tumours. Regarding the subtemporal decompression, he made a vertical incision over the temporal fossa, preferably on the side of the lesion or the right side. After cutting the soft tissues and the superficial temporal fascia he separated the muscle fibres and denuded the temporal bone to remove the bone with gouge forceps after making a hole. This decompressive craniectomy was also made on the suboccipital area for posterior fossa tumours, but in a more restricted way. In both cases the decompression was protected by muscle. The final aim was to avoid blindness and the early death of the patient due to an increase on the intracranial pressure. The decompression could be associated with the subtotal resection of a tumour located in a different area. If it was carried out as a primary intention intervention it allowed the subsequent tumour resection through a new craniotomy.

31.5 'Keyhole Surgery'

A revival of the small cranial openings for intracranial surgery, sometimes done using the trephine, was the 'keyhole surgery' [10]. This concept was introduced by Donald H. Wilson (1927–1982) in 1971. The idea was developed later by others and particularly by Axel Perneczky (1945–2009) in the supraorbital subfrontal approach to the suprasellar and parasellar lesions. 'Keyhole surgery' has been done using different cranial openings and corridors: supraorbital subfrontal, pterional trans-sylvian, temporal subtemporal, interhemispheric and retromastoidal. The concept of the 'keyhole surgery' was to reduce the size of the craniotomy to minimise the time of the cranial opening and closure, and reduce the complications related to the cranial opening. From a technical point of view 'keyhole surgery' was done using small craniectomies or trephine crowns of 2 in. in diameter. Trephines were coupled to electric or pneumatic powered motors, and had a central pin to avoid sliding in the beginning of the opening. This small pin was removed before completing the resection of a disc of bone. At the end, the bone was replaced and secured with some stainless steel wire stitches. This approach has some limitations. First is the need of a perfect preoperative planning to select the most adequate location of the cranial opening and the intracranial corridor to reach the lesion. Second, 'keyhole surgery' has always a very limited surgical field available to manipulate micro-instruments or deal with big lesions. Finally, this approach can be dangerous to deal with aneurysms and particularly solve complications such as intraoperative ruptures. All of these concerns have dimmed the use of this kind of approaches.

31.6 Craniotomy for Lesions of the Skull Base

The last field where craniotomy had to adapt to pathology was probably concerning approaches for tumours located on the skull base. The development of surgery of the skull base as a subspecialty of neurosurgery began in the 80s. The possibility to act safely on such complex lesions became true by the combination of several elements. These include, among other, sophisticated imaging techniques, a good command of the microsurgical technique, advances concerning the surgical instruments and motors, advances in neurophysiological monitoring systems, teamwork, multidisciplinary approach and knowledge of the microsurgical anatomy aimed at the approach that was learnt in the laboratory.

Lesions in this area, regardless of their type, show some common features: they require retracting the brain to remove them (which involves a risk of inducing additional neurological deficits as a consequence), and they involve vessels, causing thus a brain ischaemia or the death when they are damaged. They also involve cranial nerves, causing at best annoying and long-term neurological symptoms in the patients when they are damaged. Finally, they also involve a high risk of cerebrospinal fluid fistulas, which could cause meningitis and death of the patient. To reduce these risks and maximise the tumour resection many craniotomies were invented, reinvented and modified. The essential strategic change focused on the design of the craniotomy, which must allow a very large bone resection from the skull base to achieve a flat access to the lesion without requiring to retract the brain.

Classical craniotomies aimed at solving the intracranial pathology, basically hemispheric conditions, proved to be clearly inadequate to meet these goals. The cranial resection that is achieved by holes and cuts made with electric or pneumatic motors is only useful to open a window that allows us then to mill the bone of the skull base enough to reach the tumour. Most part of the work is often done in the epidural space. Soft tissues are cut, retracted and prepared to be adequately used for the closure. For this reason, it is quite common that pedicle periosteal or muscle-aponeurotic flaps are created during the approach stage previous to the cranial opening so that they can be used at the end of the surgery.

This new pathology developed complex and sophisticated approaches that often required many hours of work and were the reason for postoperative complications. Some examples of this were the craniotomies for combined approaches to the anterior and middle fossae or the middle and posterior fossae and their extensions to the foramen magnum or the jugular foramen. Accordingly, algorithms and approach models to the most hidden areas of the skull base were designed. The terminology used was usually confusing. The great supporters of this strategy were the pioneers of the skull base surgery, particularly L.N. Sekhar, C. Chen and O. Al-Mefty. In contrast to these complex craniotomies, another current was soon developed. It was based on keeping the old craniotomies, introducing minor technical modifications, but firmly applying the principles of the skull base surgery. M. Samii is a good example of this strategy. He continues defending retrosigmoid suboccipital craniotomy, with an enlarged field by milling the suprameatal eminence. Other examples are V. Dolenc or E. De Oliveira with the anterior clinoidectomy as an improvement of the classical and versatile pterional craniotomy.

Nowadays we are in an intermediate situation between both strategies, with families of larger or smaller approaches around the basic craniotomy that can be individualised and adapted to each specific lesion. An example of this is the family of approaches developed around pterional craniotomy that allow to treat lesions on the base of the anterior fossa, orbit, middle fossa and cavernous sinus with a mini or standard basic approach that is extended towards the frontal or temporal region, the basal enlargement of the craniotomy to expose the middle fossa by resecting the zygomatic arch, the enlargement by resecting the orbital ridge and the upper part of the orbit, and finally the orbito-zygomatic craniotomy, with the largest approach in this group. Another example is the family of approaches that is generically named *'far-lateral-approach'*. They are focused on the access to the foramen magnum but allow treating lesions that extend from the middle third of the clivus to the high cervical region.

31.7 Conclusions

All what has been pointed out summarises the current situation of the *'state of the art'* of the craniotomy in the twenty-first century and its indications. It is obvious that the indications of craniotomy have exponentially increased since the first modern craniotomy, which was invented by Wagner to treat traumatic epidural haematomas. Craniotomy is still the most used approach to the intracranial space and its pathologies. We can affirm that the success of osteoplastic craniotomy is due to the fact that when craniotomy was invented there was an emerging need for large approaches to the intracranial space that could be bigger and more comfortable than those provided by cranial openings made with trephines or enlarged burr holes. In fact, craniotomy was soon used to treat tumour and infectious pathologies that started being diagnosed by the neurologists at that time. Traumas were still a frequent indication thereof but the focus moved to tumour pathologies during the first decades of the twentieth century and then vascular pathologies were incorporated. All the indications that made up modern indications of craniotomy were gradually incorporated later.

Our personal point of view about the current approaches to intracranial lesions of any type is gathered in the book *'Abordajes neuroquirúrgicos de la patología craneal e intracraneal'*, published by José M. González-Darder, Vicent Quilis-Quesada and Evandro de Oliveira in 2016 [11]. This book explains the anatomical and technical aspects as well as the indications of the nine approaches that, from our point of view, meet the needs of most part of tumour and intracranial vascular pathologies and those pathologies located on the skull base. The craniotomy of each one is described in detail. The book particularly addresses cortical and subcortical trans-sulcal approach, bifrontal subfrontal approach, pterional-trans-sylvian approach, approach to the middle fossa, interhemispheric trans-callosal approach, lateral suboccipital approach, medial suboccipital approach, extreme lateral approach and infratentorial supracerebellar approach. We recommend to carry out osteoplastic craniotomies with free flap in all cases, using an electric or pneumatic motor to make the holes and cut the bone. Only the retrosigmoid osseous resection of the lateral suboccipital approach is made with a burr and a motor to adapt it to the patient's particular anatomy. Once the surgery is over, it is covered following a cranioplasty technique that uses a synthetic material.

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32 Craniotomy at War Times. World War I and World War II

Modern neurosurgery was just born when unfortunately it was necessary to demonstrate its importance in the two most devastating armed conflicts in the history of humanity, i.e. the First Great European War or World War I (1914–1918) and World War II (1939–1945) [1, 2]. We are going to assess more briefly other more recent armed conflicts that luckily were of lesser importance. From a neurosurgical point of view, the most relevant aspect in all these conflicts was the fact that almost all wounds were caused by high-energy firearms, the gradual introduction of antisepsis in the treatment of cranial wounds, the gradual introduction of imaging equipment and finally the better organisation of the health systems in the armies, which included neurosurgeons and neurosurgical equipment.

However, contrary to other previous historical periods the impact of the experience on the battlefields on the technique of craniotomy has been insignificant. This can be due to several reasons. The main one is that before this period of time, the main (or the only) indication of cranial surgery within the civil life was wounds and fractures of the head. For this reason, battlefields were a breeding ground to gain experience on this subject due to the casuistry. The surgeons who served in the army made use, as it is natural, of the experience gained to put it into practice with civilians. The second aspect is that in the civil life many other diagnosis and indications of craniotomies arose. They were very different from the ones applied in armed conflicts. A third element is that, even if we only consider cranial wounds and fractures, those that were caused in the armed conflicts were very different from those caused in the civil life. Injuries caused by high-energy projectiles became exclusive of wars from the twentieth century, whereas surgeons from the civil life continued treating traumas caused by blunt objects at work and by road accidents later. Due to all these reasons, the twentieth century turned the tables and instead of applying the experience gained in cranial surgery at war to the civil sphere it was just the opposite. Surgeons applied the experience from the civil life to war surgery. Some examples of this were the antibiotics or the imaging techniques. The expert neurosurgeons even ended up designing the protocols about the care of patients with cranioencephalic injuries on the battlefield. As we will see, this paradigm shift began as a consequence of the experience after World War I and was consolidated in World War II.

32.1 World War I

During the European Great War or World War I (1914–1918), the massive use of artillery and automatic rifles with high-speed projectiles meant a dramatic increase in the number of penetrating wounds in the skull and a particular focus on the treatment thereof by the surgeons.

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Shortly after the United States went to war in 1917 surgeons were specifically trained. They were sent to the front to treat cranial wounds. This way, some of these surgeons continued with the surgical training after the war as civilian neurosurgeons. This fact had a great impact as the American College of Surgeons declared neurosurgery as a surgical specialty right after the end of the war. The study of war-wounded soldiers meant a great contribution to the knowledge concerning the localisation of cerebral cortex functions by neurologists. Hence, Thierry de Martel (1875–1940) stated that they examined almost 5000 cases of cranial traumas at his department, which was located in La Salpêtrière (Paris) and was turned into a military neurological centre, between years 1915 and 1916.

It is worth commenting, as an anecdote, that Harvey Cushing (1869–1939) was among the group of North American surgeons who served in Europe adhered to a British Health Unit between years 1917 and 1918. There is evidence that he and his team operated 113 soldiers with cranial wounds for 3 months. He contributed to reducing significantly the historical mortality (from 45% to 29%) of penetrating wounds on the skull in that unit. In spite of a rumour about a possible trial in a military court after quitting abruptly in May of 1918 and being repatriated to the United States, Cushing was considered the leader of American cranial surgeons who served in Europe at that time [3, 4]. However, he only followed systematically the general principles that were accepted for cranial surgery and that prevailed in Europe by then. The effort of war surgeons particularly focused on the early treatment of cranial wounds by improving the evacuation systems and bringing the treatment of those injured to the battlefield.

However, the better results of the neurosurgical treatment of war wounded were probably due to more unspecific factors. William Williams Keen (1837–1932) compared the military surgery of the American Civil War with the recently ended World War I in 1918 [5]. He analysed the existing improvements in both historical moments and highlighted the following (in this order): the arrival of bacteriology, the knowledge of the cause and treatment of tetanus, recognising the importance of wound disinfection, the use of the Carrel-Dakin method in the treatment of infected wounds with sodium hypochlorite, general sanitary measures, the reduction and control of the typhoid fever and finally the new precision instruments and diagnosing methods. Among these instruments and methods, he includes the thermometer, the hypodermic needle, the electrocardiogram, the inhalation anaesthetics and the X-ray equipment. There were no references about changes or improvements concerning the surgical technique.

32.2 World War II

The most important improvements of World War II (1939–1945) concerning the care of cranial traumas were not due to an improvement of the surgical technique or a paradigm shift in the surgical treatment either. The reasons for improvement can be found in the early treatment of cranial wounds and the use of protection cranial helmets that were truly effective against projectiles and shrapnel and other traumatic agents.

Many models of a complex treatment close to the front lines were developed under the idea of an early treatment. They went deep in what they have learnt from World War I. This way, the British army developed the Mobile Neurosurgical Units (MNSU) that had enough material to carry out 200 interventions before having the need to be supplied again. The nine units that were working carried out about 20,000 interventions. Thanks to this the mortality of penetrating cranial wounds was reduced to half in comparison with World War I, as it went from 28% to 14%. Steel helmets were compulsory in all armies. It is curious that the designs of the helmets were very different and, for example, the British helmet provided less protection to the base of the skull than American or German helmets. Hugh Cairns (1896–1952), a British neurosurgeon who was very involved in the attention and caring organisation at war, immediately applied the use of the helmets to motorcyclists [6].

The German armed forces (Wehrmacht) also developed neurosurgical equipment in different healthcare levels [7, 8]. Not only did they care for wounded soldiers but also contributed to the training of many neurosurgeons who later focused their professional activity in the civil sphere. Many of them collaborated somehow with the National Socialist Government and, in turn, some of them suffered from retaliations after the war, whereas others didn't at all. Wilhelm Tönnis (1898–1978) was a famous German neurosurgeon. He was a general physician (*Generalarzt*) in the Luftwaffe and was very involved in the organisation of the classification or 'triage' of the wounded and their evacuation. He classified the wounded in three levels, where the dying patients or those with minimal possibilities of recovery only received a complete healthcare if they were officers or belonged to specialised units or branches. Klaus Joachim Zuelch (1910–1988) was another well-known neurosurgeon who belonged to the Wehrmacht. He developed an ambulance-armoured vehicle to give advanced care in armoured units. He equipped a special model of a half-track vehicle that transported the troops with a neurosurgery operating room inside (*Sanitaetpanzerkampfwagen–Sd.KFz 251/8 I*). To do so all the health and surgical materials had to be modified so that it fitted inside it. This vehicle travelled among the tanks along the battle line to provide immediate assistance.

Soviets report that 13% of all wounds in the war were in the head. Among them, 28.1% were penetrating wounds which multiplied by 7 the figures of previous conflicts, such as the Winter War (1939–1940) against Finland [9]. The Lieutenant-General Nikolay Nilovich Burdenko (1876–1946) was one of the most renowned neurosurgeons who actively collaborated in the care organisation too.

The theoretical organisation of North American military health service at war was based on the classical model of healthcare levels [10, 11]. There was a small tent near the front for the first aid, which basically consisted of bandages and dressings. However, small teams of experienced surgeons (surgical auxiliary teams) were taken close to the front to treat severe wounds as soon as possible later. Those injured on the skull were taken in ambulance vehicle to the evacuation hospitals with neurosurgical operating rooms. Once they had been treated there they were evacuated by ambulance, train or airplane to a large general hospital at the rearguard. Finally, they were taken by ship or airplane to a large general hospital in the United States as soon as possible later. Training programmes concerning military exercise for neurosurgeons were longer and more comprehensive than those implemented in World War I. They went from being a 10-week course to a 3-month programme that could extend by three additional months if it was necessary in the United States.

However, just like in World War I, there were no significant advances concerning the neurosurgical technique or technology applied to craniotomies as a consequence of this conflict. The general recommendations for treatment of penetrating wounds were the following: washing and shaving the head; applying local anaesthetics, chloroform or pentothal; removing foreign bodies from the wound; removing devitalised tissues including the brain; washing with saline and sulphonamide instillation in the wound; and finally closure thereof. Foreign bodies were located by X-ray equipment. Surgeons did not try to remove those ones that were very deep. Big tissue defects were repaired with aponeurotic or muscle flaps using preferably the temporal muscle. Cranioplasty was always a deferred technique that was carried out at a general hospital. The antibiotic treatment with penicillin became popular throughout the war. The higher survival rate of soldiers with severe cranial traumas forced to develop new models of physical and neuropsychological rehabilitation. It also promoted the later reparation techniques of cranial defects or cranioplasty.

On the contrary, there was a radical paradigm shift concerning the treatment of traumatic spinal injuries and, as a consequence, an impressive improvement in the life expectancy of these patients. Hence, more than 80% of those patients with spinal injuries died during the first weeks after being damaged and the rest had a very short life expectancy of just a few months during World War I. In contrast, three-quarters of the North American patients with spinal injuries survived 20 years after in World War II.

Armed conflicts have occurred after World War II but fortunately they were of lesser importance. Military medical services have also been involved in these conflicts. Among them we must highlight the Korean and the Vietnam wars between years 1950 and 1970, as well as the many wars in the Middle East. There were no significant changes again concerning the surgical technique for the treatment of penetrating wounds in the head either. In general terms, they maintained the general principle of early craniotomy for the debridement and cleaning of the wound with the removal of foreign bodies. This general principle has been questioned in each conflict but in the end it has been reaffirmed and has included proposals so that it became less aggressive concerning the removal of foreign bodies. This position is justified by the better localisation of these elements thanks to the computerised axial tomography, which allows a more direct access, and by the recommendation of not removing foreign bodies if it involved an additional risk for the patient. In these cases, the risk of infection or epilepsy does not seem to increase significantly. For this reason, if they are found later it is not mandatory to operate the patient again. The helicopter evacuation, in which the wounded is picked up from the battlefield itself, allows to move field hospitals away from the front so that those injured can receive a more complete, specialised and definitive assistance. This model had to be introduced by the North Americans during the Vietnam War as there was not a well-defined battlefront that could justify the maintenance of the classical healthcare levels of the military health service. This same situation remained during the recent conflicts of Israel, Lebanon, Afghanistan or Iraq [12].

Current recommendations include a minimal debridement of small penetrating wounds in patients with a good level of consciousness and without a progressive neurological deficit. Complex surgery in critical patients must be carried out in centres placed at the rearguard after a rapid and safe evacuation. These centres must be fully equipped with diagnostic and therapeutic resources, including intensive care units. Antibiotic and antiepileptic treatments are essential to reduce mortality. Vascular lesions are a cause of intraoperative mortality. For this reason, they must be exhaustively confirmed or excluded by means of an angiography in those cases when the projectile's path can affect great vessels, when there is a particularly large haematoma or if it is suspected during the surgical examination of the wound [13, 14].

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33 Craniotomy: Illustrative Cases

Nowadays it is possible to find on the Internet a great amount of testimonies from anonymous people who underwent a craniotomy. They describe first hand the experiences and feelings they lived concerning their illness and the surgical procedure. It is increasingly frequent that the media gather information from public figures who have suffered from neurosurgical problems. Some of them also underwent craniotomies.

Some examples were the actress Sharon Stone (1958–) who suffered from an intracerebral haemorrhage in 2001 due to the rupture of a giant cerebral aneurysm, which was treated by embolisation, or the famous Spanish golfer Severiano Ballesteros (1957–2011), who suffered from a glioma that put an end to his life. Some of these cases have been studied in detail in neurosurgical publications due to the historical relevance of the figure or the circumstances of the treatment. An example of this was the pianist Clara Haskil (1895–1960), who underwent surgery due to a suprasellar tumour in 1942 [1]. Marcel David (1898–1986) carried out a frontal craniotomy with local anaesthesia in Marseilles to treat her. The patient experienced headaches and bitemporal hemianopsia. The results were excellent as the patient could go back to the stage 3 months later, still wearing a bandage on her head.

The two presidents of the United States who were murdered died as a consequence of being shot in the head. None of them could be surgically treated. A detailed report about the cranial injuries of the North American president John F. Kennedy (1917–1963) was published in several articles in the journal *Neurosurgery* [2–4]. President Kennedy was murdered after being shot several times on the 25th of November of 1963. The wounds on the skull are described in detail and the neurosurgical and forensic implications are discussed. The president died before undergoing a craniotomy. In the previous chapter we reported that Abraham Lincoln (1809–1865) was killed on April 15, 1865, by a shot in the occipital region, dying hours later without receiving surgical treatment [5].

To illustrate the craniotomy, we have chosen some clinical cases with a very different clinical evolution. They were described by renowned authors at the time such as Keen, Krause or Cushing. The last case refers to the one described in a famous novel written by the Hungarian writer Frigyes Karinthy, who described first hand the craniotomy he underwent for the treatment of a brain tumour.

33.1 Gasserian Ganglion Resection by a Middle Cranial Fossa Approach

William Williams Keen (1837–1932) described six cases of trigeminal neuralgia in a report presented to the Philadelphia County Medical Society in 1896 [6]. They were surgically treated

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following the Hartley-Krause technique. The aim of this technique was the complete resection of the Gasserian ganglion and its branches. After some technical considerations and the description of the difficulties and the surgical complications the author explains the cases one by one. We have selected the first one.

Dr. K., a 41-year-old man, had been suffering from a trigeminal neuralgia for 13 years and he had already undergone 13 surgical interventions to solve it, including the resection of part of the mandible and some branches of the nerve. Keen carried out the intervention in two different times separated by 3 days. In the first stage the temporary osteoplastic flap was lifted. When doing so, the anterior branch of the middle meningeal artery was harmed. The dura mater was damaged and the posterior branch of the middle meningeal artery was sectioned when enlarging the posterior margin. Both arteries were ligated *'after much trouble'*. When they lifted the temporal lobe, the bleeding was so massive that the surgical field was wrapped with gauzes covering it with a total of 37 × 6 inches, i.e. 232 square inches. The patient's temperature reached 100.8 °F and the respiratory rate decreased to 6–10 per minute during the immediate post-operative period. The patient showed a slight aphasia. A breaking up of the Gasserian ganglion was carried out during the second intervention. The subsequent evolution was good and the patient showed no more symptoms except for some painful discharges that persisted.

It is discouraging that this was the best surgical treatment that the best surgeons from other times could offer to their patients with trigeminal neuralgia. The case described is a good example. The patient risked his life due to the design of the craniotomy itself in spite of being treated by skilled surgeons who were experts on the treatment. Keen described in the monograph six cases that were operated. Among these cases, four of them required surgery in two different times due to a massive bleeding of the middle meningeal artery during the craniotomy or the cavernous sinus when lifting the temporal lobe. This forced them to wrap the wound with gauzes. One of the patients died during the post-operative period and other three patients showed corneal ulcers that required the eye enucleation in one of them. The pathological study of the resected specimens did not show the trigeminal elements expected during the resection in all cases. The results were almost always partial. Nowadays no surgery with these results would be carried out.

The trigeminal neuralgia is effectively treated by microvascular decompression of the trigeminal root since Janetta's observations in 60s. Shortly after it was determined that the physiopathology of the trigeminal neuralgia was due to the development of abnormal connections between the nerve fibres in the so-called *dorsal root entry zone* (DREZ) of the nerve in the brainstem due to the mechanical effect of microvascular compression. Current surgery is carried out by a retrosigmoid mini-craniotomy, separating the DREZ of the nerve from damaging vessels. Theoretically, there are no sensory or motor disorders in the trigeminal region. Those patients for whom the mentioned surgery involves a high general risk can benefit from alternative treatments that are minimally invasive, such as percutaneous neurolysis or radiosurgery.

The standard or enlarged pterional craniotomy to the middle fossa is used nowadays when approaching lesions in Meckel's cave or in the cavernous sinus. Moreover, the complex anatomy of Meckel's cave, the cavernous sinus and the dural layers of the area are now known. The approach can only be understood to be carried out with a microsurgical technique. The first step of the extradural stage of this approach consists of identifying, coagulating and sectioning the middle meningeal artery in the foramen spinosum and then identifying the exit point of the third branch of the trigeminal nerve through the foramen ovale. Excluding the middle meningeal artery does not involve any problem and the haemorrhage from the cavernous sinus can be controlled by fibrin glue injections with relative ease. This craniotomy is not currently used to treat the trigeminal neuralgia, as it was substituted by the microvascular decompression of the trigeminal root in the cerebellopontine angle.

33.2 Right Central Gyrus Meningioma

Fedor Krause (1857–1937) includes a great amount of illustrative clinical cases concerning the surgeries he describe in his two-volume book *'Surgical operations of the head'*, English translation of the *'Chirurgie des Gehirns und Rückenmarks'* published in 1907 [7]. He also illustrates these cases clearly in beautiful prints. We have chosen an interesting case of a meningioma on the central gyrus that is brilliantly described and solved.

A 41-year-old man starts suffering from repetitive nocturnal seizures at the age of 31. He had been diagnosed with epilepsy, which was attributed to a bullet lodged in the chest wall after being shot with a firearm when he was 15. The projectile was located by an X-ray and was removed without incidences. However, neurological symptoms persisted. The seizures always showed the same manifestations as time went by. They involved dry mouth followed by an abnormal feeling of vibration, numbness, loss of sensation or stiffness on the left side of the face that were occasionally accompanied by contractions on the hemi-tongue and ipsilateral labial commissure. The clinical manifestations were followed by numbness on the left hand, starting from the thumb, which went up in the arm until reaching the neck. The frequency of the seizures was 1–3 times a month, although several seizures could occur in the same day. The patient was treated with bromide. The patient showed continuous numbness of the shoulder, jaw, hemi-cranium and left auricle.

According to the above-mentioned information, an expandable slow-growing tumour or tumour-like process located on the right central gyrus was clinically diagnosed. The neurological assessment carried out by Oppenheim on the 18th of January of 1910 states that the patient shows a slight hemiparesis, positive Babinski sign and lack of abdominal reflex.

The intervention was carried out in two successive surgical times, on the 20th and the 31st of January of 1910, following the already described Krause's general guidelines for craniotomy. After lifting the bone, the vessels of the dura mater were spotted. They were abnormally numerous, tortuous and large. They were ligated without incidences. The initial craniotomy was enlarged with gouge forceps, reaching the following measurements: 87 mm of width and 96 mm of height. The dura mater was opened in the second intervention. A reddish-yellowish tumour was found after lifting it. It was growing from the deep layer of the dura mater and has been originated there or in the arachnoid. The tumour was easily detached from the brain and it was lifted 'en bloc' together with the dura mater, which is finally sectioned to release the lesion after ligating some vessels. A depression with the size of half a small apple was left on the brain. The dura mater was not replaced and the osseous flap was put back to its original position without requiring any wrapping or drain. The diagnosis was an 'encapsulated fibrosarcoma' or meningioma.

The post-operative period was satisfactory, with no infections or cerebrospinal fluid fistula. The patient got out of bed 3 weeks after and 5 days later he was discharged from hospital. The hemiparesis and the sensory disorder improved rapidly and he went back to work on the 10th of March. There were no data about new seizures.

It is an example of a big-size meningioma with long-term irritating focal neurological symptoms and short-term compressive symptoms. There was no intracranial hypertension syndrome. The topographic diagnosis and the intraoperative localisation of the lesion are perfect, without requiring any additional help from the imaging techniques. The surgical technique and the clinical result are excellent. The description of the technique and the intraoperative findings are accurate. Nowadays it is probable that an imaging study would have diagnosed a meningioma of the central sulcus with a high degree of reliability after the first seizure. The current recommendation would be neurosurgical treatment, regardless of the more than likely clinical control of the seizures with anticonvulsant treatment. The intervention would probably have been carried out by neuronavigation and intraoperative neurophysiological monitoring of either motor function by motor-evoked potentials and direct electrical cortical stimulation and of sensory function by somatosensory potentials. The craniotomy would have been smaller and the dura mater would have been repaired by a biologic dural substitute. The relationship between the bullet lodged in the chest wall for years and the patient's epilepsy is nowadays intriguing.

33.3 Right Cerebellopontine Angle Tumour

Harvey Cushing (1869–1939) told his experience with tumours in the cerebellopontine angle in his book *'Tumors of the Nervus Acusticus and the syndrome of the cerebellopontile angle'* [8]. He gathered 30 confirmed cases and 35 suspected cases of acoustic neuroma during his 10-year experience at the John Hopkins Hospital in Baltimore and his 4-year experience at the Peter Bent Brigham Hospital in Boston. The description of the cases is exhaustive, both concerning the clinical information, the evolution, the intervention, the pathological studies and the autopsy when applicable. It constitutes an example of clinical data collection that should be emulated. Each case is accompanied by photographs of the patients, the pathological report, necropsy findings when applicable and critical feedback. We have chosen case I.

HS, a 43-year-old male, is referred by his doctor and he is admitted at the hospital due to a headache. He reported that he had a long-standing hearing loss in his right ear, which was attributed to a chronic pathology of the middle ear. He had been suffering from suboccipital paroxysmal headache crisis accompanied by yawns for 3 years. He had recently started to show an infraorbital neuralgia that was not alleviated after teeth removal. He then showed instability while walking and started falling down. Finally, he suffered from vision disorders, obnubilation and slurred speech and was prostrated in bed during the last months. He highlights from the physical examination the following aspects: bilateral optic atrophy, anosmia, exaggerated deep reflexes, nystagmus, ataxia, instability and Romberg, hypaesthesia in the trigeminal area, palsy of the VI cranial nerve, deafness and affected lower cranial nerves with dysarthria, all on the right side. There were no radiologic studies. He was operated on the 16th of January of 1908. However, the anaesthetics were not well tolerated and he started showing a difficult and irregular breathing, followed by cyanosis. The surgery was aborted before exposing the cerebellum and the patient died 3 days after.

The necropsy report described a marked bilateral herniation of the cerebellar tonsils and a significant hydrocephalus. The lesion had a size of 4 × 4 × 3.5 cm and was initially diagnosed as 'dural endothelioma' or meningioma. However, after it was reviewed in 1916 it was finally diagnosed as a 'typical acoustic neurofibroma'.

The major aspects, according to Cushing in his self-critical remarks of the case, are incongruous clinical data, such as incomplete deafness of several years of evolution with no signs of tinnitus or vertigo; very advanced clinical symptoms with severe intracranial hypertension syndrome that even causes blindness; and mistaken diagnosis about the type of tumour, which is finally described as a 'neurofibroma'. He eventually admits that it was his first case of a tumour in the cerebellopontine angle and his first attempt to expose the cerebellum for any cause, and that *'the outcome was not encouraging'*. Cushing thinks that the bad evolution was due to the difficulties when positioning the patient during the surgery and the anaesthesia. In this regard, he states that, in the end, *'the experience proved a valuable one'*, as it allowed him to develop some supports for the shoulders that improved the patient's position during the surgery of this kind of lesions.

Many of Cushing's reflections are still considered valid. Fortunately, it is nowadays exceptional that a patient undergoes surgical treatment in such a deplorable clinical condition. However, a late diagnosis is still frequent in cases of long-standing hypoacusis. If this happens, the first step consists of solving the hydrocephalus with an external ventricular drain or an endoscopic third ventriculostomy. It is curious that Cushing described the hydrocephalus in the autopsy but he did not consider it relevant when justifying the ominous patient's evolution. The lack of deafness, tinnitus or vertigo is unusual in acoustic neuromas and more frequent in meningiomas. The huge size of the lesion explained the symptoms of the patient and even now would imply a serious prognosis.

33.4 Frigyes Karinthy's Cerebellar Tumour

The Hungarian writer Frigyes Karinthy (1887–1938) wrote about his personal experience concerning the diagnosis and the surgical treatment of a brain tumour from which he suffered himself in the book *'Utazás a koponyám körül'* ('A journey round my skull'), which was published in 1938 [9]. He was operated by the Swedish neurosurgeon Herbert Olivecrona (1891–1980) in Stockholm in 1936. Karinthy was born in Budapest and after doing some courses in sciences and medicine he devoted himself to journalism and writing. He became one of the main Hungarian writers of that time. The book describes first hand the experiences, fears, dreams and hopes of a patient with a brilliant and ironic intelligence as he faced the challenge of coping with the diagnosis and treatment of a brain tumour. He describes literarily the symptoms of his illness and the surgical treatment he underwent. Karinthy is also known worldwide for setting out the so-called hypothesis of the 'six degrees of separation' in 1930. He suggests that any person on earth can be connected to any other person in the world by a series of people with no more than five intermediaries, i.e. six connections. He suddenly died a year after his intervention.

Karinthy, a 48-year-old writer, suddenly started suffering from auditory hallucinations, which he describes as 'trains', followed by frequent migraines. Later on, he also had vertigo and loss of consciousness attacks without falling to the ground or seizures. He finally started suffering from nausea and vomiting, deviation to the right while walking and visual and writing disorders. At that time, he was successively diagnosed with an otologic disorder, intoxication due to the nicotine of tobacco as well as psychological disorders. He was recommended psychoanalysis. An ocular fundus exam showed bilateral papilledema and a brain tumour was then suspected. He was examined by neurologists in Budapest and Vienna for several weeks. He got skull X-rays done and a lumbar puncture was suggested but fortunately it was not done in the end. Meanwhile the papilledema progressed, reaching up to seven dioptres. His visual acuity got worse to such an extent that he almost went blind. He started experiencing confusion stages.

Finally, doctors concluded that he had a tumour on the right cerebellar hemisphere, probably an angioma. The patient moved to Stockholm to be operated by Olivecrona. The intervention was carried out with local anaesthetics and in prone decubitus position. A gas ventriculography was carried out first. To do so, two burr holes were made in the operating room and the patient was taken to the radiology service. Karinthy described the experience of the first hole as follows: *'Thunder sounds. A huge steel drill penetrates inside my skull, howling like a whistling that becomes faster, higher and more strident. It must be the electric drill! … A hell of a noise, earthquake. How can I resist this? I don't even have time to notice if it hurts. Suddenly, the noise stops with a slight rebound. The drill has completely penetrated and it means that its bit is spinning in the air'*. After the ventriculography the patient went back to the operating room and he was placed face down. His head was firmly fixed with surgical tape. They carried out an approach by a longitudinal incision on the middle line and a new burr hole. He described his feelings again: *'The whistling of the drill is now more infernal and tenacious than ever'*, *'The continuous vibration gets me completely deaf'*, *'At last the unbearable thunder stops'*. After drilling, the suboccipital craniotomy is completed with gouge forceps, which Karinthy notices as follows: *'An strong and wild pull'*, *'Tension, pressure, break, tear … something breaks with a thud. The same happens just an instant later. Tension, pressure, break, tear. Many, many times, one after another. The subsequent breaks make me think of the moves used to open canned food, the noises, however, remind* *me of closing a wooden box. I notice how the surgeon breaks the bone in large pieces'* … *'In the last one, which seems to be the first vertebra, he has vacillated; it resisted for a long while, until he got to remove it by pulling'*. The intervention continued with the removal of the tumour and he was discharged from hospital 6 weeks later with no apparent neurological deficits, with an excellent clinical improvement and recovery of the visual acuity. The book does not tell anything about the nature of the removed lesion.

We have selected this case due to the brilliant description the patient gives about his experience during the surgery, as well as due to the way patients with brain tumours were diagnosed and treated in Europe during the 30s. We must highlight that the brain tumour suspect is based on the papilledema. However, other type of exam is neither proposed in Budapest nor in Vienna, except for the skull X-rays and the lumbar puncture, which was not carried out. The localisation of the tumour is based on the results obtained after several weeks of neurological studies, but it was very accurate. Arteriography had been invented by the Medicine Nobel Prize laureate Antonio Egas Moniz (1874–1955) in the year 1927. Air ventriculography and pneumoencephalography had been invented by Walter Dandy (1886–1946) 10 years before. Dandy was nominated for the Medicine Nobel Prize for this contribution. Nowadays all these study methods had been substituted by magnetic resonance imaging. Arteriography is only done when a vascular malformation or hemangioblastoma is suspected.

Surgery was carried out by Olivecrona by means of a bilateral suboccipital approach and craniectomy with gouge forceps from an initial burr hole. The posterior arch of C1 was resected. The intervention was perfectly carried out following the principles applied in that time. Nowadays a similar case would have been managed as follows. The presumptive clinical diagnosis would have been a tumour of the posterior fossa with intracranial hypertension syndrome derived from an obstructive hydrocephalus. An endoscopic third ventriculostomy would have been carried out nowadays and the patient would have undergone surgery a few days later, once the intracranial pressure had been controlled. The diagnostic ventriculography that was carried out on Karinthy had this same therapeutic effect. Many surgeons still started the surgery after placing an external ventricular drain for decades, even after this diagnostic procedure had been abandoned. Nowadays the posterior arch of the atlas is not usually resected in medial suboccipital craniotomies. The craniotomy can be ipsilateral in the case of cerebellar hemispheric lesions.

Karinthy did not give many details about the intraoperative findings in his book. He did not describe the pathological report of the removed lesion either. The neurologists from Vienna made the diagnosis of an angioma after auscultating the occipital area of the patient. Some vascular lesions can produce a murmur that can be heard by the patient or by auscultating the skull. However, Karinthy's lesion does not seem to be an arteriovenous malformation at all as it did not produce an audible murmur. Only dural arteriovenous fistulas typically produce an audible murmur, but it does not seem that the patient suffered from a dural fistula either. The neurologists also hypothesised that the lesion could be cystic-like but there is not enough information in the novel that lets us know how they came to this conclusion. The good evolution of the patient suggests that the lesion, which was probably a tumour, might be a low-grade glioma or hemangioblastoma. Karinthy stated that he was taken some photographs during the post-operative period for a scientific publication. If we assume that this information was true, it is possible that the lesion was an angioreticuloma (hemangioblastoma) as Olivecrona published a review of 70 cases that underwent surgery years after, in 1952 [10]. The description of the symptoms and the management of Karinthy's case exactly correspond to the description of the symptoms and treatment of these tumours given by Olivecrona in his article. Karinthy might be one of the six patients that he reported that had died between 1 and 6 years after the surgery due to intercurrent diseases and the only one who showed no sequelae after surgery.

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34 'State of the Art' of the Craniotomy in the Early Twenty-First Century and Future Development

34.1 State of the Art of the Craniotomy Nowadays

The changes in the surgical technique over the last decades have focused in turning the osteoplastic craniotomy with pedicle bone flap into an osteoplastic craniotomy with free bone flap (Fig. 34.1). We have reached this point after a gradual inclusion of slight modifications of the initial technique. A single osseous-muscle-pericranial flap was obtained in craniotomies with pedicle bone flap at the beginning. Two flaps were lifted subsequently. One of them was a pericranial flap which reached the galea aponeurotica and the other was an osseous-muscle flap. Finally, the current technique consists of obtaining a free bone fragment. Soft tissues can be lifted in one or two flaps. A single flap includes all soft tissues and incorporates the periosteum. When two flaps are elevated separately, one of them includes periosteum and muscle and the second one the galea aponeurotica and skin.

In the old osteoplastic craniotomy with pedicle bone flap the osseous fragment was always a single piece as the aim was to place it back to its original position once the intracranial procedure was over. Pedicle bone flaps in complex areas such as the posterior fossa and skull base were difficult and they soon were substituted by craniectomies by bone removal in small fragments using the gouge forceps. The osseous cranial defect that was made with this technique was not covered with bone at the end of the procedure, as it was protected enough by the reposition of the muscle and the soft tissues. Nowadays the size and manoeuvrability of high-speed motors allow making osteoplastic craniotomies with free bone flap in almost any area of the skull, including the posterior fossa and skull base. We routinely use this method in all craniotomies, except for the retrosigmoid approach to access the cerebellopontine angle. In this particular approach, we make the required skull opening by milling the bone with a spherical burr that has a diameter of 6 mm.

It is neither clear enough who suggested the free bone flap instead of the pedicle bone flap nor when was it done. Boldrey and Cone, from San Francisco, already reported the use of the *'free bone osteoplastic craniotomy'* in a series of 50 cases in 1941 [1]. Ray and Parsons, from New York, published a series of 100 cases in 1947 [2]. They pointed out that they already replaced cranial bone flaps infiltrated by benign tumours, such as osteomas or meningiomas, after removing and boiling them for 3–10 min, according to Nafzinger's technique, which was described in turn in 1937.

The free bone flap became popular some years after, during the 70s, thanks to M. Gazi Yasargil (1925–). Yasargil describes his own surgical technique for interfascial pterional craniotomy or frontotemporal sphenoidal craniotomy in his spectacular treatise *'Microneurosurgery'*, which

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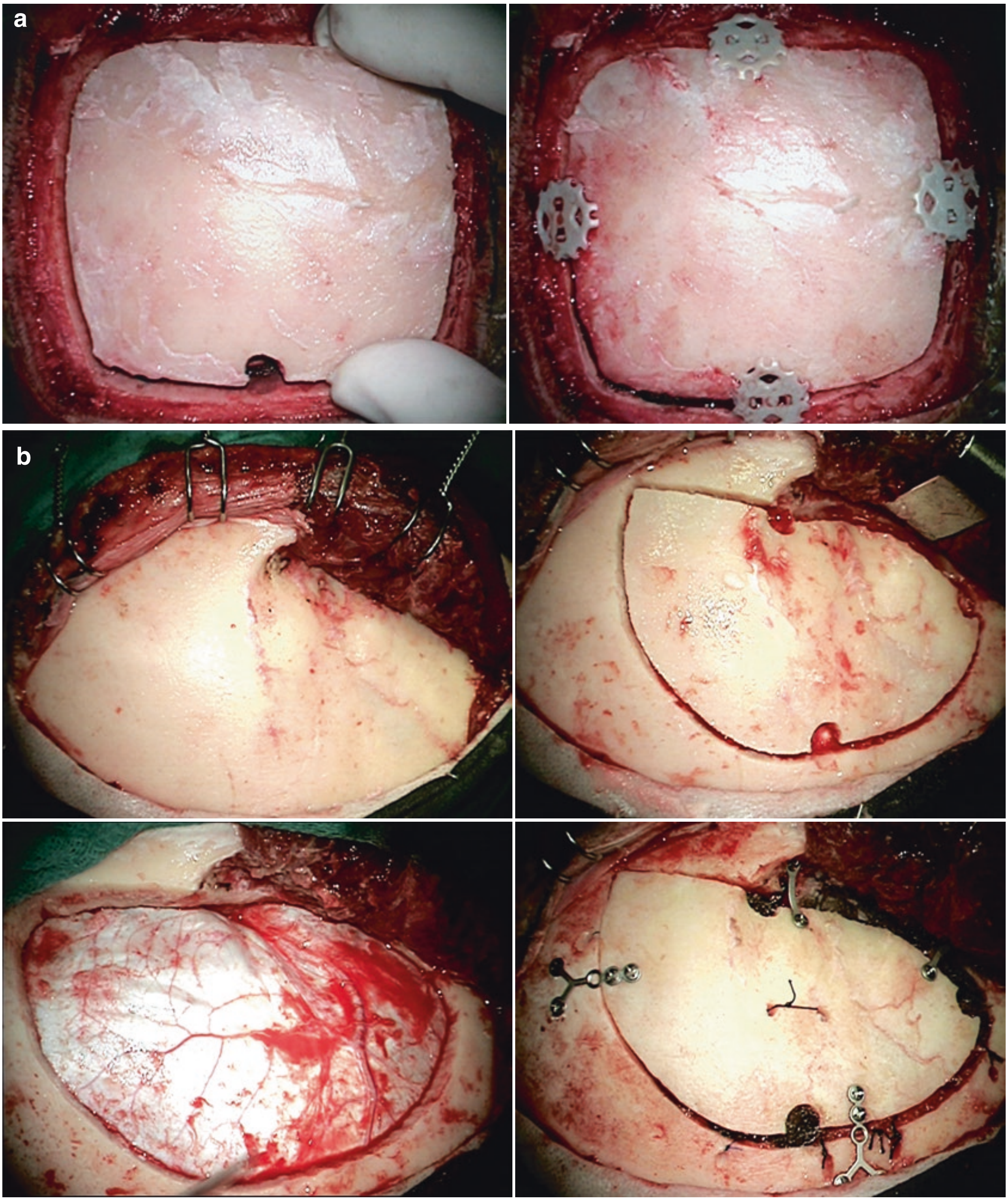

Fig. 34.1 Modern free bone flap osteoplastic craniotomies made with a high-speed electric-powered motor. (**a**) The first craniotomy is a right parietal craniotomy of small size for the resection of a subcortical tumour. There is only one hole made with a 4 mm spherical bur. After surgery, the flap is replaced by four PEEK cranial fixators. (**b**) The second one is a left pterional frontotemporal craniotomy for a cavernous sinus tumour. Three holes have been made with a 12 mm perforator, one in the anterior cranial fossa and another in the middle cranial fossa above and below the lesser wing of the sphenoidal bone, and the third in the temporal fossa, below the temporal line. The bone between the first two holes becomes thin and bankrupt due to leverage. The bone cutting was done with a high-speed vertical saw. With a burr, the lesser sphenoid wing is lowered before the dura is opened. The bone is replaced at the end of the intracranial time with several titanium miniplates. The osseous defects of the holes can be filled with the bone sawdust obtained during opening. (**c**) The third craniotomy is a middle suboccipital craniotomy extended over the transverse sinus for an infratentorial supracerebellar approach to a pineal tumour, showing the free bone flap obtained

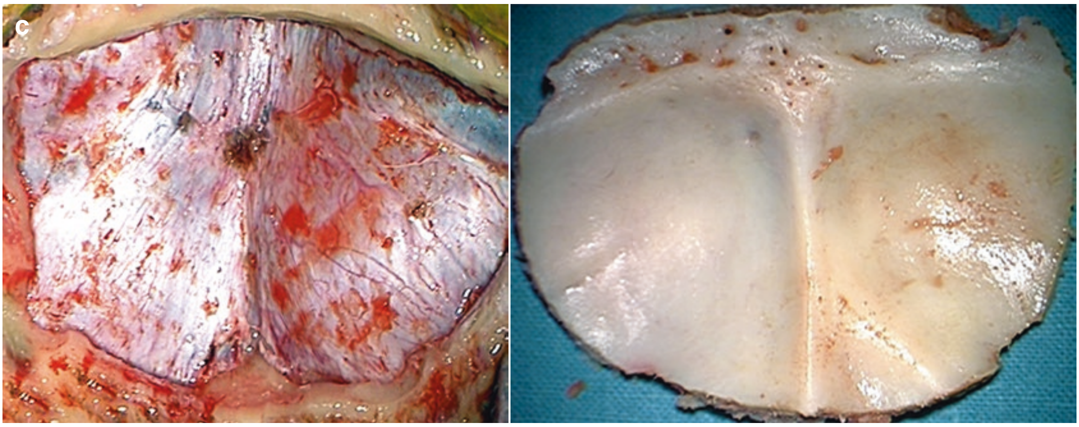

Fig. 34.1 (continued)

was written along many years [3, 4]. After making an interfascial dissection of the temporal muscle the author carefully separates the temporal muscle from the bone in the temporal fossa. The bone is completely denuded and free from any muscular insertion or attachment. In volume I, which was edited in 1984, he starts the opening of the bone by making four holes and he states that *'for many years … burr holes were drilled by hand, but since 1976 an electric powered perforator which stops automatically as the dura is encountered has been employed'*. He continued the craniotomy with the Gigli's saw by cutting the bone between the holes linearly. He then uses again *'a high-speed electric drill'* to mill the bone on the base of the osseous flap and make a *'gentle, atraumatic, and precisely limited fracture'* that allows him to lift a free osseous flap, separating it from the dura mater. The rest of the craniotomies that are described in the same volume also involve a free bone flap. The holes are made with the help of a perforator attached to a low-speed electric motor and the areas between them are sometimes cut with a Gigli's saw and other times with an electric vertical saw.

Yasargil describes the technique of the same pterional craniotomy in a different way in volume IVB of this same treatise, which was published some years later, in 1995. Now, he makes a single hole with the motor in the temporal fossa. He uses the electric saw to cut towards the frontal region until reaching the upper edge of the lesser wing of the sphenoid bone. Then he cuts towards the temporal region until reaching the lower edge of the lesser wing of the sphenoid bone. He also uses a high-speed electric drill to make the bone thinner over the lesser wing, which he carefully fractures to lift again a free bone flap.

Free bone flap has many advantages. Among them, they allow more versatile craniotomies that are adapted to each case to be treated. They also involve less post-operative osseous bleeding risk because the bone is not vascularised. Free bone flaps have better cosmetic results, as they avoid the displacement of the osseous flap due to the muscle traction during the post-operative period. It is also a fact that pedicle flaps get infected more often and that haemorrhagic complications like epidural haematomas are more frequent as well. Finally, the procedure to obtain a pedicle flap is more arduous and takes more time than a free osseous flap. The disadvantages of the free flap include a higher risk of bone devitalisation as it is free from the periosteum and has no contact with soft tissues, but actually this is not a concern in the neurosurgical practice. The problems of free bone flaps are related with the attrition of the muscle when it is detached from the bone. This is relevant in the temporal fossa, where there is a higher risk of ischemia and denervation of the temporal muscle, and thus atrophy and fibrosis. The consequences are cosmetic defects and a dysfunction of the temporomandibular joint.

One of the first and main historical arguments to justify the osteoplastic craniotomy with pedicle bone flap was the importance of keeping the vitality of the bone by means of its connection to the periosteum, the cranial muscles and, ultimately, the vascularisation from the pericranium. This was one of the strongest arguments for Wagner when he designed his temporary craniotomy [5]. When a bone loses its connection to its blood supply, just like what happens with the free bone flap, all of its cells die and only the matrix and the inert mineral structure remain. They can be occupied again by osseous cells later. Some modern studies aimed at proving the vitality of the bone in the pedicle flap when compared to the free flap have shown that, indeed, the pedicle bone maintains its vitality whereas it disappears in the free flap.

Taking into consideration some of these arguments and in spite of the spread of the osteoplastic craniotomy with free flap, there are still publications in renowned journals that support traditional osteoplastic craniotomy, with minimal modifications of the procedure [6]. In this regard, Kim and Delashaw published in 2010 a modification of the pterional craniotomy in which they suggested lifting a temporary osteomyoplastic flap and substituting the pterional burr hole by a triangular osteotomy made with a fine cutting tip [7]. This avoids the depression of the pterional trepan, which is so frequently observable and noticed by the patients who consider it as a cosmetic defect. The muscle that is adhered to the bone also allows a better cosmetic result than the one achieved when it is separated from it, as it retracts during the cicatrisation stage. Finally, the replacement of the triangle of bone at the end of the surgical procedure is like a key that grants the correct positioning of the osseous flap. The only imposition of the method is that it requires an epidural drain as it has been proved that there is a higher risk of venous bleeding when the osseous muscular flaps are replaced.

Other variations of the technique of modern craniotomy have been an indirect consequence of improvements and contributions to other fields. The haemostasis of soft tissues is not a problem thanks to the bipolar coagulation. No preventive haemostasis methods are used any longer. The cranial fixation with Mayfield clamps that are attached to the surgical table makes it easier to cut the bone and retract soft tissues with hooks or hitches that are applied to rubbers or springs. Microsurgery allows a clean and careful surgery. The better control of the patient during surgery by means of the intraoperative monitoring and a more efficient anaesthesia allow the surgeon to carry out a safe and unhurried intervention. Finally, the technical possibilities of repairing the dura mater, the cranioplasty and the periosteal, muscle or cutaneous flaps allow to solve complex designs of craniotomies, complications or particular needs imposed due to the patient's anatomy or pathology.

34.2 The Future of the Craniotomy

Nowadays craniotomy is the core surgical technique of neurosurgery and, at present, the only exclusive procedure of our specialty. Craniotomy has now become one of the steps (the first one) of any neurosurgical approach to intracranial lesions. Modern craniotomy is the final result of the numerous contributions and developments that we have reviewed. Current craniotomy is a fast and comfortable technique for the surgeon. It is safe for the patient and provides a great value considering its risks, economic cost and benefits.

From a conceptual point of view, the aim of craniotomy is to open a large window on the skull to treat an intracranial disease. Hence, neurosurgeons nowadays do just what Wagner did when he introduced the 'temporary craniotomy' [5]. From a technical point of view, there are two essential differences. The first one is the way the osseous flap is obtained. Nowadays it is done with high-speed motors instead of using a chisel and a mallet. The second one is that we now create a free osseous flap instead of a pedicle one. Of course, many other surgical aspects related to craniotomy have changed as well. Some have already been discussed and others have not. The evolution and the changes related to the opening and closure of soft tissues have not been reviewed in this work. The fixation systems to replace the osseous flap or to repair cranial defects or carry out a cranioplasty have not been discussed either and so haven't many other topics that are directly related to the approach, such as those systems that fix the head to the surgical table, which were very important and had many consequences in the technique of craniotomy and its instruments.

An important factor concerning the rapid evolution of modern craniotomy is that it was carried out (and it is still carried out) in a period of time in which the information exchange is the basis of medicine and where the information moves around at a high speed. This way, novelties and improvements are known and adopted increasingly faster. A sociological model called the technology adoption life cycle was described 50 years ago. It explains how the groups accept or adopt new technologies. The described model follows a normal distribution and predicts that there is a first small group of people who immediately accepts new technologies (*'innovators'*), accompanied by another group who quickly accepts them (*'early adopters'*). A large group (*'early majority'*) is quickly added later, followed by another large group who does it even later (*'late majority'*). A small residual group with a very conservative view is left (*'laggards'*). They adopt new technologies very late. In order to measure the degree of acceptance of a new technology it is possible to determine how long does it take for the technology to be adopted by a quarter of the group to which it is aimed. As it could be expected, it has been observed that this time is increasingly shorter. Hence, the electricity, which was introduced in the United States in 1873, took 46 years to reach a quarter of the population there whereas the cell phone, which was presented in 1983, only took 13 years.

This same model can be applied to the technology involved in craniotomies, where the successful modifications spread and are accepted increasingly faster within the neurosurgical community. Cranial trepanation was carried out following the same technique and using the same technology based on the use of drillers derived from the *'terebra'* and the *'modiolus'* from the fourth century BC until the end of the nineteenth century. There was not much innovation during these 2500 years but when it appeared the number of supporters was not high enough for a paradigm shift. Wilhelm Wagner (1848–1900) suggested the craniotomy that persuaded all cranial surgeons in a short space of time of barely three decades in 1889. The adoption of the craniotomy with a manual trepan to make the holes and the Gigli's saw to cut the bone was done at the same speed. In both cases it is possible to identify isolated groups of *'laggards'* with critical and conservatory points of view when it came to adopting the already mentioned craniotomy and new instruments. Harvey Cushing (1869–1939) had undoubtedly a driving role to accept these changes. A new paradigm shift in the technique happened during the 70s, that is, only four or five decades after the universalisation of the osteoplastic craniotomy with pedicle flap made with Gigli's saw. It was possible thanks to the osteoplastic craniotomy with free flap made with high-speed motors, which was adopted by most neurosurgeons of the developed world even faster.

When analysing the craniotomy from a technological point of view, we must admit that instrument solutions that are currently used make the most of the best technological developments that are now available. However, we must admit likewise that these technologies and solutions will soon become obsolete as others will be launched. In addition, this will happen very fast.

Now that we have reached the end of this work, it is time to hypothesise about the future of craniotomy. The first line of reasoning would be to identify which are the current emerging technologies that have started to be implemented in craniotomy and envisage their future options. In this regard, robotics applied to neurosurgery might seem a good option. Nowadays there are commercially available robots that allow to accurately place intracranial electrodes and catheters through burr holes. They follow orthogonal trajectories that are controlled by neuronavigation. Some examples are the ROSA by Medtech, the Neuromate by Renishaw or the da Vinci by Intuitive Surgical. Some simple procedures have been carried out by remote commands when the neurosurgeon was located from a distance. However, all these developments are nothing but improvements and evolutions of the classical stereotactic surgery and modern neuronavigation. There are already some experimental and rudimentary works that allow us to imagine the possibility of creating large cranial openings by robots [8]. The studies carried out in animals have achieved craniotomies with a predetermined shape and size by drilling and connecting many small holes that made up the cranial window. Following this line of reasoning, it is not hard to imagine a future in which the craniotomy and the intracranial procedure can be totally or partially carried out by robotic mechanical systems that are programmed and controlled by the neurosurgeon.

Another alternative future of craniotomy that is completely different to the one mentioned could be abandoning it due to its uselessness. This could happen in a utopian situation where intracranial pathology that nowadays requires surgery could be solved without any surgical intervention thanks to the development or invention of other treatment methods. This line of thought has already had many milestones during the last decades. Lars Leksell (1907–1986) published the first scientific article about radiosurgery in 1951 [9]. This treatment technique allows to treat different types of intracranial lesions by a formed radiation beam without requiring craniotomy. The first treatment was carried out in 1955. Nowadays thousands of patients have been treated of benign tumours, metastases and arteriovenous malformations, avoiding thus thousands of craniotomies. Fedor Serbinenko (1928–) published the first embolisation of intracranial vascular lesions with detachable balloons in the Soviet literature in 1971 and in international Western literature in 1974 [10]. There was an exponential development of these endovascular treatment techniques of aneurysms and brain vascular malformations that do not require a craniotomy in the subsequent decades. Once again, they allowed to treat thousands of patients and avoided thousands of craniotomies. There has been a significant decrease in the number of traffic accidents in developed countries during the last decades. This is due to the preventive safety campaigns and a better design of the vehicles and roads. This has allowed to reduce radically the number of craniotomies due to haematomas and fractures caused by cranial traumas. The studies made with nuclear magnetic resonance spectroscopy allow us to characterise brain tumours with a high reliability. If effective pharmacological treatments that avoid volumetric resection of tumours are developed as a first step of the therapy, a great deal of craniotomies will be unnecessary in the future to remove gliomas.

All these changes seem to disrupt the craniotomy as a basic procedure of neurosurgical activity. However, paradoxically the total amount of craniotomies increases with time as the mentioned facts seem not to have a significant impact. Hence, a study that compared neurosurgical activity in the United States between years 1993–1999 and 2000–2006 shows that the number of craniotomies increased by 18% between both periods, as they went from 92,048 to 108,801. This increase is higher than the expected according to the increase of the North American population, which was only by a 5% between both periods. The causes that might have influenced this increase in the number of craniotomies are many. Among them, we must highlight not only the increase of the population itself, but also the higher life expectancy of the population, the better and faster access to diagnostic and treatment means thanks to universal public health systems, the fact that patients trust on the ability of current medicine to solve complex problems and the greater sensitivity of imaging techniques to detect intracranial pathology [11].

A more recent study published by Baker and Amin-Hanjani in 2004 supports this trend [12]. The authors of the study gathered the DRG 1 diagnosis (Diagnostic Related Group 1: craniotomy other than trauma in patients aged >17) that was included in the database of hospital discharges Nationwide Inpatient Sample (NIS), which represents about 20% of all non-federal hospitals in the United States. It showed an increase by 49.6% of discharges with DRG 1 between years 1988 and 2001, with a total amount of 251,733 patients and a total number of 1,311,508 admissions in the United States. This means 93,679 cases per year. In addition to these cases of craniotomy, we must take into consideration those craniotomies carried out in patients of less than 17 years of age and those carried out in cranial traumas.

All diagnostic subgroups of the above-mentioned study have an increased incidence. Non-ruptured aneurysms have increased by 186% and acoustic neuromas by 790%. These are indeed indications of endovascular therapy and radiosurgery. The main percentage of indications of craniotomy includes vascular pathologies of all types (31.2%) and brain gliomas (27.2%). The increase of craniotomies exceeds the one that would correspond according to the adjusted increase of the population, which would be less than half of the observed one. For this reason, we can hypothesise that other factors can affect, such as the increase of neurosurgeons, increase of diagnosis due to a massive increase on the amount of studies with CT and nuclear magnetic resonance, better availability and access to hospital beds, increase on the age of the population or the fact that people are more worried and ask for treatment of asymptomatic lesions.

A more important fact than the increase of the number of craniotomies is that the mean length of hospital stay has significantly decreased from 18.1 days in 1988 to 8.4 days in 2001, yet it has been stable since 1997. Moreover, hospital mortality has decreased by 31% as it went from 10.9% in 1988 to 7.5% in 2001, in spite of the significant increase in comorbidity of patients.

All these data prove that cranial openings are still necessary for the treatment of those patients with an intracranial neurosurgical pathology and that it will probably be useful for many years. Craniotomy has a long history, is in good health and will probably continue to be an essential neurosurgical procedure for generations.

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