Child's Nervous System (2023) 39:2729–2735
https://doi.org/10.1007/s00381-023-06090-0

REVIEW

Neuroendoscopy: history, endoscopes, and instrumentation

Henry W. S. Schroeder[1] · **Spyros Sgouros**[2]

Received: 26 June 2023 / Accepted: 17 July 2023 / Published online: 5 August 2023

Abstract

Introduction Endoscopy was first employed in the surgical treatment of neurosurgical diseases early in the twentieth century, but did not become an established practice for a long time, mainly because of poor technology and clinical results. After a slow re-appearance in the 1980s, the 1990s saw an explosion of techniques and instrumentation. Continuing technological improvement has led to further expansion of surgical techniques and indications for use of neuroendoscopy.

Discussion The expansion of ventricular endoscopy has led to significant understanding of CSF disorders. Aqueduct stenosis as cause of hydrocephalus and arachnoid cysts are an example of pathologies, the concept and understanding of which now is considerably enhanced, due to the application of neuroendoscopy in their treatment. Management of loculated hydrocephalus has been facilitated considerably with the use of the endoscope. The concepts of aqueductoplasty, septostomy, and foraminoplasty of the foramina of Monro and Magendie emerged, which were previously unknown. Skull base surgery, especially surgery for craniopharyngioma, has seen dramatic improvement in results with the use of the endoscope. Coupling of the endoscope with neuronavigation has expanded technical capabilities even further. Overall, we can do a lot more with the endoscope now in comparison to 30 years ago.

Conclusion We should always remember that the endoscope is only a tool. Its use has indications and limitations related to its design and our ability to extract the maximum, in the context of its shortcomings. Further technological advances will push surgical frontiers even more in years to come.

Keywords Neuroendoscopy · Neuroendoscopes · Rod-lens endoscopes · Fibreoptic endoscopes · Chip-on-the-tip endoscopes · HD · 3D · 4 K

Introduction

Neuroendoscopy was first employed in the surgical treatment of hydrocephalus early in the twentieth century by pioneers such as Walter Dandy, but it did not become an established practice for a long time, mainly because of poor technology and unsatisfying clinical results. The 1910–1920s could be called the invention phase. After decades of neglect, neuroendoscopy has been enjoying a sustained resurgence since the late 1980s. After a slow re-appearance in the 1980s, the 1990s saw an expansion of techniques and instrumentation. We could call the 1980s the re-invention phase, the 1990s the expansion phase and the 2000s the era of consolidation. Further expansion followed by the introduction of High Definition (HD) video cameras in 2007 [1]. This improved visualisation contributed to the rapid development of endoscopic endonasal skull base surgery.

The history of neuroendoscopy is paralleled by the evolution of neuroendoscope design. The current design of neuroendoscopes dates back to the early days of cystoscopes, at the beginning of the twentieth century. Technical development has resulted in gradual improvement in handling and performance. The evolution of neuronavigation equipment has made its use routine in neuroendoscopy and pushed even further surgical abilities and applications. We can do a lot more a lot better with a neuroendoscope today in comparison to 30 years ago.

History of neuroendoscopy

Philipp Bozzini (1773–1809), a physician from Frankfurt, developed the first endoscope, the so-called "Lichtleiter" at the beginning of the nineteenth century [2]. He announced it on July 2, 1805, in the Kaiserlich

✉ Spyros Sgouros
ssgouros1@gmail.com

1 University Medicine Greifswald, Greifswald, Germany

2 National and Kapodistrian University of Athens and Department of Neurosurgery, "Iaso" Children's Hospital, Kifisias Avenue 37-39, Athens 151 23, Greece

Privilegierten Reichsanzeiger, Nr. 36. In 1806, he published accurately technical details [3]. The light source was a candle. In 1873, the instrument maker Gustave Trouvé (1839–1902) of Paris developed an electrical light source at the distal tip of the endoscope which improved the illumination tremendously [4]. But only the combination of electrical light source and endoscopic optics made by Maximilian Carl Friedrich Nitze (1848–1906) initiated the modern area of endoscopy [4]. In 1887, Nietze in Vienna operated for the first time using a glass lens cystoscope, with the help of an incandescent light source. The first neurosurgical endoscopic procedure was probably done by the urologist Victor Darwin Lespinasse (1878–1946), a friend of the neurosurgeon Allen B. Kanavel, at Northwestern University in Chicago in 1910 [5]. Two children with hydrocephalus had coagulation of the choroid plexus with the aid of a cystoscope. One child died after surgery, but the other survived 5 years. Lespinasse did not publish it but presented it in front of a local medical society. It was cited in a foot note in the book "The Principles of Neurological Surgery" by Loyal Edward Davis from 1936 [6–11]. Kanavel was mentor for Loyal Edward Davies and had sent him to Cushing at Johns Hopkins for neurosurgical training. Walter Edward Dandy (1886–1946) from the Johns Hopkins Hospital in Baltimore is considered to be the "father" of neuroendoscopy [12, 13]. Already in 1918, he inspected the lateral ventricles with the aid of a nasal speculum and removed the choroid plexus in 4 children. He used a head mirror for illumination. Three children died 2 to 4 weeks after the surgery. The fourth child was doing well 10 months after surgery without progression of the hydrocephalus. In 1922, Dandy reported about "cerebral ventriculoscopy" at the Johns Hopkins Hospital Medical Society [14]. Temple Fay and Francis C. Grant from Philadelphia were the first to take endoscopic photos from the ventricles in November 1922 [9, 15].

Mixter is credited to have performed the first endoscopic third ventriculostomy in 1923. Encouraged by Dandy who reported the open ventriculostomy via a sub frontal approach in 1922, he tried an endoscopic ventriculostomy initially at a brain cadaveric specimen. On the 6th of February 1923, he performed the first endoscopic third ventriculostomy on a 9-month-old infant using a urethroscope. Within the first 10 days, the head circumference decreased in size. Further developments came in 1931 by Burman from New York who performed endoscopic inspections of the spinal canal in cadaveric specimen [16]. Other neuroendoscopes were developed by Putman from Boston in 1934 [17] and Scarf from New York in 1935 [18].

An important step in the endoscope development was done by Guiot from Paris in 1963. He used for the first time an external light source which was transmitted by a quartz crystal rod which was fixed adjacent to the optic [19]. Guiot performed the first endoscopic third ventriculostomy in Europe in 1963. Additionally, he used an endoscope in transphenoidal pituitary surgery.

However, the endoscopic techniques could not gain popularity because of poor image quality and insufficient instruments. Additionally, the development of valve-regulated shunt systems in the early 1950s [20] offered a less risky and more successful treatment of hydrocephalus which was the main indication for neuroendoscopy. Furthermore, the introduction of the operating microscope into neurosurgery providing binocular view was clearly superior to the poor optics of the endoscopes. Theodore Kurze at the University of Southern California performed the first microneurosurgical operation on August 1, 1957, on a 5-year-old child with a facial nerve schwannoma [21].

A milestone was set by the English physicist Harold H. Hopkins who submitted his solid rod-lens construction of endoscopes to the patent office on July 16, 1959. Compared to the traditional glass lens system, the rod-lens optic has air lenses which improved illumination and field of view while reducing the endoscope diameter. The rod-lens endoscopes are still providing the best optical quality until today in their current form. Additionally, Hopkins designed the glass fibre bundles which are integrated in the fibre optics [12]. Huw B. Griffith from Bristol developed the first neuroendoscopic system based on the rod-lens concept in the 1970s. The endoscope had a diameter of 4.5 mm. Griffith performed plexus coagulations, tumour biopsies, and aqueductoplasties [22, 23].

In 1973, Takanori Fukushima introduced the neurofiberscope into clinical practice [10]. However, renewed interest was only expressed in the 1980s by neurosurgeons who are now considered modern day pioneers. In the beginning of the 1980s, Ludwig M. Auer from Austria introduced a ventriculoscope and started in 1983 with intracranial neuroendoscopy. In Europe, André Grotenhuis (Netherlands), Philippe Decq (France), Jacques Caemaert (Belgium), Michael R. Gaab (Germany), Dieter Hellwig (Germany), and Axel Perneczky (Germany) reported first results. Decq, Caemart, Gaab, and Perneczky designed specific ventriculoscopes for intraventricular applications. Pioneers in the USA included Kim Manwaring, Kerry Crown, Wesley King, Marion Walker, Charlie Teo, and Alan Cohen.

Encouraged by Griffith's 1986 article "Endoneurosurgery" in Advances and Technical Standards in Neurosurgery, Michael R. Gaab from Hannover, Germany, started with neuroendoscopy in 1987. In collaboration with Karl Storz and Co KG, Tuttlingen, Germany, he developed a universal neuroendoscopic system in 1989 [24]. Gaab pioneered endoscopic brain tumour surgery [25, 26].

Encouraged by reports on angioscopies, Dieter Hellwig and Bernhard B. Bauer from Marburg, Germany, used thin fiberscopes in stereotactic tumour biopsies and coined the term "Minimally Invasive Endoscopic Neurosurgery" (MIEN) [27–29].

Axel Perneczky in Mainz, Germany, used endoscopes in a variety of procedures as an adjunct to the microscope, creating the concept of endoscope-assisted microneurosurgery [30].

Oka from Japan designed a ventriculoscope in 1990 [31] and was the first one to report endoscopic aqueductoplasty [32]. Oi designed a handy rigid-rod neuroendoscope for free-hand manoeuvering [33].

The introduction of mini video cameras in the late 1980s has pushed the acceptance of neuroendoscopes since a sterile video chain could be assembled. In 2002, the first digital camera was introduced, in 2007 the first HD camera and in 2017 the first 4 K camera. The progress in optical resolution and colour fidelity led to an expansion of the indications for endoscopic procedures. Especially, the rapid progress in endonasal skull base surgery was triggered by improvement of visualisation.

Endoscopes

Rigid endoscopes

While the dedicated neuroendoscopes of today represent an evolution of the cystoscopes of the 1920s, modern manufacturing techniques have allowed the creation of smaller diameter rod lenses, which enabled the reduction in size of the endoscopes. Now, there are rod-lens endoscopes with external diameter of 4 mm or less that include a working channel, and even narrower scopes with fibreoptics with and without a working channel. This makes them more suitable for work in children and less traumatic overall.

One small but important change has been the angle of the optics. Originally in continuation to the long axis of the rod lens (straight vision), in many endoscopes today, the ocular apparatus is at an angle to it with the use of a coupling prism (angled vision), giving arguably better handling of the whole system (Fig. 1). Furthermore, different angles of view are available with 0°, 30°, 45°, 70°, and even 120°.

The light available at the operative field at the tip of the endoscope has improved significantly over the years with the advent of fibreoptic cables that "conduct" the light from the "cold" light source to the endoscope. The resulting improved illumination has made significant difference to the operating surgeon and is one of the main advantages of the endoscope over the microscope. The best light source is xenon light because it resembles sun light. But nowadays, mostly LED light sources are used because the heat generation is less.

The most important improvement has been on the camera system. In the 1920s, and even in the re-invention of endoscopy in the 1980s, the surgeon had to look directly through the eyepiece at the end of the rod lens (direct vision). From the early 1990s, there is a digital camera coupled to it. The camera attached to the endoscope and sterile-draped allowed a sterile video chain which reduced the risk of infection dramatically and improved the handling and ease of use of the whole endoscope system. The technological advance of the digital cameras, which goes hand-in-hand with the progress of computers and electronics, has made a dramatic change in neuroendoscopy [34]. Further improvement is expected to come from miniaturisation of the camera.

A very recent development is the chip-on-the-tip technology which is used on flexible scopes. Although the image quality is less than that of the rod-lens scope attached to a HD camera, it is much better than the image quality of the old fiberscopes. Unfortunately, they cannot be used in Europe so far because of the autoclave requirements for effective sterilisation against prions.

Flexible endoscope

The development of the flexible endoscope has been less dramatic. Flexible endoscopes borrowed technology from the gastroscopes using flexible optical fibres, but their application in the small narrow confines of the brain has not been

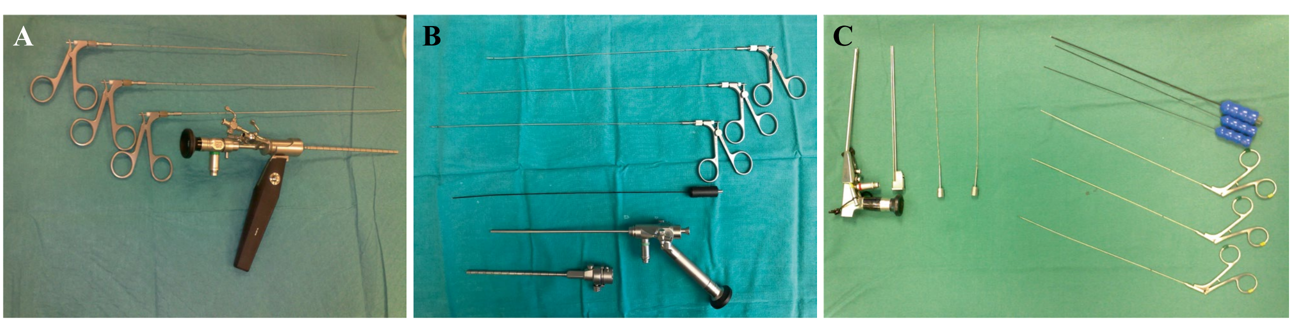

Fig. 1 **A** Storz Oi Handy Pro endoscope system with external diameter 4×2 mm with its instruments (scissors, biopsy forceps) (Storz, Tuttlingen, Germany). **B** Storz Little LOTTA endoscope system with the view piece at 45° to the rod lens with its instruments (scissors, biopsy forceps, monopolar diathermy) (Storz, Tuttlingen, Germany). **C** Aesculap Minop endoscope system with the viewpiece at 90° to the rod lens with its instruments (scissors, biopsy forceps, monopolar, and bipolar diathermies) (Aesculap, Tuttlingen, Germany)

very successful. Their picture quality is inferior to the rod-lens rigid endoscopes; their manoeuvrability is limited and not user friendly; and they have only one side port for all uses. They were in vogue in the early 1990s. Although they are still used by many neurosurgeons, it would be fair to say that they have fallen out of favour, and certainly they have not been developed any further. Flexible endoscopes available in the market are more than 2 decades old designs and are expected to be phased out.

Instruments

Another field of progress has been the development of purpose-design surgical instruments for the neuroendoscopes (Fig. 1). The availability of suitable monopolar and bipolar diathermies can provide haemostatic control when working in the ventricular system. This is limited in comparison to the microsurgical technique, and often, intraoperative haemorrhage during a ventricular procedure leads to the premature ending of the operation. Equally, suction through the endoscope is of limited power. In contrast, haemorrhage during transnasal skull base work is easier to control and has much less significance as it takes place in an open space extracranially. It is rare to have to abandon a transphenoidal endoscopic hypophysectomy because of bleeding, unless the intracavernous part of the internal carotid artery has been injured. The development of other equipment, such as scissors, biopsy forceps, and probes of various types, gives the neuroendoscopist the ability to biopsy tumours or even remove them if they are not haemorrhagic (e.g. colloid cysts), divide adhesions and open cysts, and, in general, perform a much wider spectrum of procedures in comparison to what was possible 30 years ago [35]. It should be said though that the endoscopic biopsy forceps have small "cup" and can only yield small samples, with a corresponding risk of false histology results [36]

A significant innovation is the integration of the neuroendoscopes with image guidance—neuronavigation systems. This gives increased abilities to perform tasks that otherwise would not be attempted, for fear of causing surgical damage. Multi-loculated hydrocephalus is easier treated endoscopically with image guidance, which allows confidence of access in the presence of distorted ventricular anatomy (Fig. 2). Equally, for extended skull base approaches, image guidance is of paramount importance [37]. Further improvement is likely to come in this field as image-guided systems develop further.

User interface needs further improvement. Currently, the surgeon has to follow two screens in front of him, the endoscopy video screen and the neuronavigation screen, while his hands are working at right angle to his line of vision (Fig. 2). This remains an ergonomically disadvantageous position. Technological improvement hopefully will facilitate the life of the surgeon.

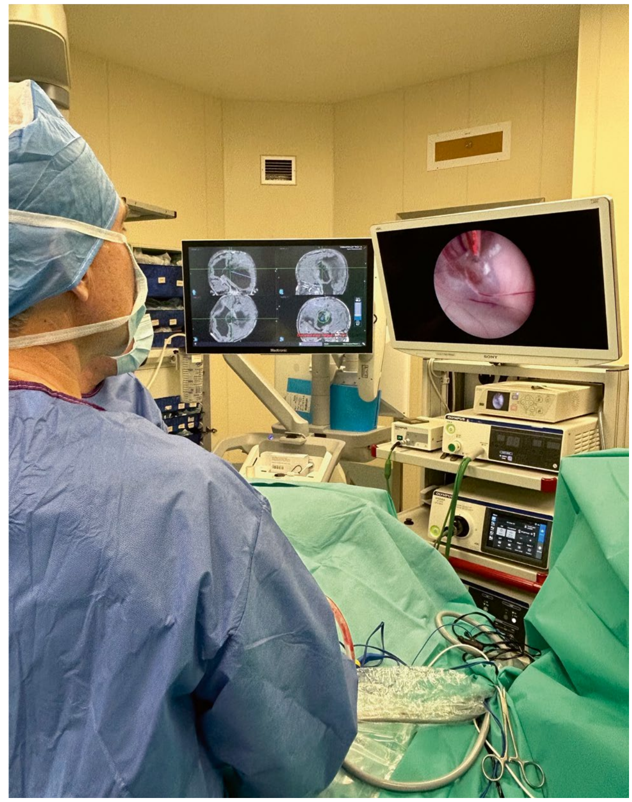

Fig. 2 Ventricular endoscopy performed in conjuction with neuronavigation. The case is that of fenestration of multilocated ventricular system in a child with post-haemorrhagic hydrocephalus. The surgeon has to follow two computer screens while his hands are working at right angle to his line of vision. This is an ergonomically disadvantageous position

New developments such as robotic and 3D endoscopes are not in wide use yet; hence, one cannot comment on their contribution to neuroendoscopy. They are considered as the next frontiers of progress [34].

Applications of neuroendoscopy

Ventricular endoscopy

The use of the endoscope gave us new insights on CSF physiology. The characterisation of aqueduct stenosis in its full form came only after the widespread use of endoscopic third ventriculostomy in its treatment. Prior to that, all forms of hydrocephalus were treated by shunting, with only occasional use of stereotactic third ventriculostomy guided by ventriculography. The use of the endoscope and, in parallel, the use of MR imaging to assess the result of endoscopy gave us the knowledge to differentiate between aqueduct stenosis and other forms of infantile hydrocephalus and greatly enhanced our understanding of CSF physiology [38–42].

The use of the endoscope in the management of CSF circulation disorders has been pathophysiology-driven. Following the introduction of the endoscope in the management of CSF disorders, the concepts of aqueductoplasty, septostomy, and foraminoplasty of the foramina of Monro and Magendie emerged, which were previously unknown [39]. Similarly, the utilisation of endoscopic techniques in the surgical management of intracranial arachnoid cysts improved our understanding of their dynamic nature with respect to CSF movement in and out of them and the presence of a valve-like mechanism on their wall. Increasingly, the endoscope is employed in the management of intraventricular tumours [26, 35]. The combined use of neuronavigation has expanded capabilities in this field.

Ventricular endoscopy carries some risks. A small but appreciable risk exists of severe neurological damage after third ventriculostomy, damage to the basilar artery, the fornix, the basal ganglia, or the hypothalamus [38, 43, 44].

Skull base endoscopy

The use of the endoscope in extended skull base tumour resections improved access to difficult areas and technically made possible extent of surgery that was previously either not possible or carried significant morbidity, and this is achieved with less complications and overall better clinical outcome.

During skull base procedures, a substantial part of the skull base has to be drilled in order to reach the target. The complication rate from endoscopic extended skull base approaches can be high, with CSF leak being the most frequent, but also risk of possible neurological damage of cranial nerves as they are exiting the skull base foramina [37, 45]. Additional use of neuronavigation is mandatory these days and reduces complications significantly [37].

Transnasal endoscopic work has seen significant expansion in adult patients. Pituitary tumour surgery, which previously was performed with the microscope, nowadays, is performed endoscopically almost exclusively as the endoscope offers far superior visualisation [46, 47]. Craniopharyngioma surgery has been revolutionised with the use of the endoscope. Transnasal endoscopic resection allows better resection possibilities with lower morbidity from hypothalamus and stalk damage and better visual outcome form reduced manipulation of the optic chiasm [48]. In children, skull base pathologies that are amenable to endoscopic surgery are rare overall. Pituitary tumours are rare. Craniopharyngioma is commoner in children than adults, but often in children, it has a significant suprasellar component, making transnasal access difficult. Other extended skull base tumours are rare. The issue of pneumatisation of the sphenoid sinus always comes in consideration. Some neurosurgeons have reported transnasal work even in children as young as 2 years, by drilling the non-pneumatised sphenoid sinus. This remains an issue of controversy and discussion currently.

Spinal endoscopy

Spinal endoscopy has been increasingly employed in adults with degenerative pathology. In children, where spinal pathology is either malformations or neoplasms, there is currently limited indication for use of the endoscope. Practically, spinal endoscopy is not employed in children currently.

Endoscopy in craniosynostosis

The endoscope has been increasingly used in the last decade in surgery for correction of craniosynostosis. It was initially introduced in sagittal synostosis, but now, it is employed in metopic and coronal synostoses. It allows the realisation of strip craniectomies through small incisions, avoiding the large skin flaps previously employed, sparing the patient all the associated morbidity. Currently, only strip craniectomy can be performed with the endoscope. Complex reconstructive procedures require large open exposure. Good results have been demonstrated with the use of the endoscope especially in sagittal synostosis, when performed in the first 3–4 months of age, and the technique is gaining popularity. The associated use of cranial orthosis (helmet) remains an issue of further study.

Future directions

Further improvement in visualisation will come from development of the computer part of the imaging system of the endoscope. 3D visualisation has already been implemented but needs improvement. It is reasonable to think that in the next decade that will come in to everyday practice. Integration with neuronavigation is expected to improve, which will promote applications and manoeuvring even more.

Conclusion

Neuroendoscopy has seen dramatic expansion in the last 3 decades and revolutionised the treatment of hydrocephalus and related CSF disorders. Skull base surgery has expended to previously unthought off levels. Further technical surgical improvement will follow equipment development.

Author contribution Henry Schroeder and Spyros Sgouros wrote the main manuscript text. Spyros Sgouros prepared the figures. All authors reviewed the manuscript.

Declarations

Conflict of interest The authors declare that they have no competing interests as defined by Springer.

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The material of this paper has not been published elsewhere and is not in consideration for publication elsewhere.