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Traumatic injuries: organization and ergonomics of imaging in the emergency environment

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Abstract Management of trauma patients relies on a simple but obvious concept: Time is life! This is a challenge to the emergency radiologist in his evaluation of the radiological admission survey of severe trauma patients, since the latter need a quick and thorough survey of craniocerebral, cervical, thoracic, abdominal, and limb lesions. This article reviews the architectural design and the management strategies required to fulfill this purpose. Whereas plain films and ultrasonography have precise but limited indications, multislice spiral CT (MSCT) shows an increasingly preponderant role in the imaging evaluation of trauma patients, as demonstrated through three examples (aortic, spine, and craniocerebral trauma). Multislice CT affords a comprehensive assessment of trauma patients' injuries and allows for their categorization according to the severity of traumatic lesions. With respect to the MSCT data volume, the emergency radiologists have to modify the strategies in their examination reading and result transmission, with a growing role attributed to two- and three-dimensional reconstructions. The emergency radiologist's role is thus of prime importance in the management of trauma patients, and this all the more so since development of interventional radiology affords therapeutic procedures alternative to surgery. Trauma radiology and emergency radiology on the whole will assert themselves as consistent and thorough areas of subspecialization.

Keywords Radiology department · Hospital · Trauma centers · Organization and administration · Organizational policy · Organizational objectives · Time management

Epidemiology of trauma

In industrialized countries, trauma represents the third leading cause of death, behind cardiovascular diseases and cancers [1]. Trauma is a major concern, since it mainly affects young patients. Indeed, 48% of trauma patients are aged 25–44 years, trauma representing the main cause of death in this age group [2, 3]. In the U.S. and western European countries, trauma most often results from traffic accidents, whereas falls, mainly on the work site, recreational accidents, and violence account for the other causes [4, 5, 6]. Trauma due to motor vehicle accidents or to violence is clearly related to alcohol consumption: Up to 65% of the victims of traffic accidents are found with positive alcoholemia, 26–50% exceeding the legal limit of 0.5–0.8‰ [3, 7].

Overall trauma mortality ranges from 4 to 20% [6]. Fifty percent of the casualties die from head injuries, 20% from hemodynamic or respiratory complications, both at an early stage after trauma. The remaining 30% die later, from infection and sepsis, with subsequent acute respiratory distress syndrome and multiple-organ failure [8, 9, 10]. Furthermore, trauma induces considerable morbidity and has a major socio-economic impact.

Globally, it is responsible for approximately 30,000 disability days per 100,000 persons annually in the U.S. [2, 3]. Two billion U.S. dollars are the estimated short-, mid-, and long-term costs of trauma in Switzerland, where 600 deaths and 30,000 severe injuries are recorded annually for a population of 7,600,000 inhabitants and 4,600,000 motor vehicles [4].

Since trauma mainly affects young patients and has a considerable socio-economic impact, trauma, as well as its management, constitute a major challenge. Our purpose is to focus on our management concept of the trauma patients in the emergency room (ER), based on a 13-year experience. On the other hand, extra-hospital management is beyond the scope of this paper and is summarized by the aphorism, “Time is life: the smaller the delay until patients’ admission at the ER, the better the prognosis indeed.” The superiority of helicopter medical service over ground medical transportation was extensively demonstrated during the Korean War and later during the Vietnam War. A 52% reduction in the mortality rate was observed in trauma patients treated at the site of injury and transported to the trauma center by air medical transport, when compared with standard pre-hospital management services [11, 12].

Design of modern emergency radiology units

Trauma patients’ admission to the ER is characterized by the intervention of a multidisciplinary teamwork involving intensivists, anesthetists, neurosurgeons, maxillo-facial, thoracic, and abdominal surgeons, as well as orthopedists. Among all these specialists, radiologists and imaging play an increasingly preponderant role, both in the categorization of trauma patients according to the severity of their lesions and in the making of clinical decisions at each management step. This growing role of radiology does not only have to be considered in the ER, but also in the resuscitation room (RR), in the operating room (OR), and in the intensive care unit (ICU). Thus, on admission in the RR, trauma patients undergo a cervical spine radiograph before possible endotracheal intubation, as well as screening chest X-ray and abdominal ultrasonography. Once hemodynamically stabilized, a CT survey is performed to assess brain, thoracic, and abdominal visceral lesions. The admission survey ends with digitized or analogic radiographs for upper and lower limb fractures. In the OR, some surgical procedures are performed under fluoroscopic or sonographic guidance. Moreover, conventional radiological or CT follow-up examinations are mandatory after surgery or during the ICU stay, in order to allow for early detection of complications and check-up of tube and line position. Fluoroscopic, sonographic, and CT guidance is more and more frequently required in interventional procedures such as tube positioning. Finally, information provided by CT regarding, for instance, the site and importance of an active hemorrhage is greatly profitable to diagnostic and therapeutic interventional maneuvers.

Availability and proximity of emergency radiology units (ERU) are evidenced by the preponderant and increasing role of imaging in the management of trauma patients.

Availability of fully equipped radiology units located within the ER, where emergency patients can immediately be evaluated, without interfering with scheduled outpatients, goes along with the mandatory around-the-clock presence of a resident and a senior resident in the ERU. The senior resident’s role is to direct technologists in the selection of imaging protocols and in the performance of the examinations. They are also in charge of rapidly providing clinicians with a diagnosis regarding the trauma patients’ condition. Furthermore, the senior resident is responsible for the coordination of trauma patient management in the ERU, where non-urgent diagnostic and nursing procedures often interfere with those of imaging and slow down trauma patients’ admission survey as well as subsequent mandatory, sometimes life-saving, therapeutic maneuvers. Finally, the senior resident has to remind the non-radiologist colleagues that radiology rooms are devoted to efficient management of trauma patients and do not constitute a recreational area! One or several senior radiologists must also be on call for diagnostic supervision and sophisticated interventional procedures. The deadline for the senior radiologist’s intervention should not exceed 15–30 min.

Proximity must govern the architectural design of ER and of its four components – RR, ERU, OR, and ICU – which should ideally be next to each other. Every effort should be made to reduce transportation times. The fitting-out of trauma patients and their monitoring for transportation are very difficult and time-consuming. At our institution, transportation of trauma patients represents 30–50% of the total time spent in the ERU. Monitoring of trauma patients during transportation is often more complicated and occurring complications more difficult to manage, with possible life-threatening consequences. Moreover, in order to prevent displacement of fractures, mainly of spine fractures, transfer of trauma patient, for instance from his bed onto the CT or angiotable, requires a minimum of four persons, who have to be recruited among the technologist and nursing pools. Presently, their number is limited for economic reasons, which is a further argument in favor of the minimization of transportation times. Our 13-year experience demonstrates that preparation and transportation times, for instance in a CT unit, can be reduced by 50% with an adequate organization and training of the technologist team.

Computed tomography as the cornerstone of trauma radiology

The primary and challenging goal of the ideal imaging technique in an efficient ERU is to reach the correct diagnosis as fast as possible. It must neither delay other diagnostic and therapeutic procedures, nor interfere with the monitoring of hemodynamically unstable trauma patients. It must afford simultaneous and accurate evaluation of brain, chest, and abdomen.

Spiral computed tomography (SCT), and, even better, multislice SCT (MSCT), show all these advantages and have asserted themselves as the gold standard imaging technique in the ERU (Fig. 1). Clinical relevance of CT compared with conventional radiology is high. It represents an adequate screening procedure to detect hemomediastinum, aortic lesions, pericardial effusions, occult pneumothoraces or pleural effusions, free peritoneal fluid, hepatic, spleen, and renal trauma, as well as spine fractures. It displays up to 83% of additional abnormalities requiring undelayed treatment, chest tube insertion being the most common procedure [1, 13, 14, 15, 16].

The CT examination in a trauma patient is performed with his arms placed along his sides. Because of frequent associated upper limb fractures, the patient's arms cannot be positioned above his head. The subsequent artifacts are minimized by data acquisition according to the spiral mode, especially with multi-slice technology, and do not interfere with the interpretation of the so-acquired MSCT survey. Minor streak artifacts may be induced by metallic components such as skin ECG electrodes, nasogastric or nasotracheal tubes, or life-support equipment, but never justify their removal [1, 13, 14, 15, 16].

At our institution, complete realization of a cerebral, cervical, thoracic, and abdominal MSCT survey averages 40 min, with the following distribution: 45% for transportation; 35% for CT data acquisition itself; and 20% for data management by the technologist, including two-dimensional coronal and sagittal reconstructions. The 14 min required for CT data acquisition is much longer than the performance of the cerebral, cervical, thoracic, and abdominal MSCT sequences themselves, which account for less than 3 min when added to each other. The 11-min mismatch relates to the frequent interruptions of data acquisition required by monitoring of trauma patients, their frequent motion and/or agitation, and resuscitation maneuvers required by hemodynamic instability. The 14 min required for CT data acquisition can hardly be shortened. On the other hand, our experience has revealed a possible saving of up to 20–25 min in the duration of the MSCT survey in trauma patients by improving technologist work ergonomics and especially by a systematic overlapping of patient transportation to the bed and data management; thus, in daytime at least, one technologist should be in charge of the MSCT data processing and printing, whereas another one should collaborate with the ER nursing team to transport the patient.

Other imaging techniques in the ERU

Other imaging techniques are being progressively replaced by MSCT.

Conventional radiology (Fig. 2) is required for the survey of the cervical spine on admission. It is usually limited to a lateral view, with consideration of a possible urgent tracheal intubation; however, it is well recognized that plain lateral views of the cervical spine are reliable to depict severe unstable fractures or dislocations but do not prove accurate enough to rule out more subtle ones, which makes CT mandatory. Similarly, CT is more accurate in displaying thoracolumbar spine fractures.

Supine chest X-ray remains the most important imaging examination for the initial assessment of thoracic injuries and their management. Its sensitivity is indeed very high with respect to hemomediastinum, tension pneumothoraces, large hemothoraces, flail chests, and subcutaneous em-

Fig. 1 Multislice CT has asserted itself as the gold standard imaging technique in the emergency department

Fig. 2 Portable X-ray unit used in the emergency room to evaluate cervical spine before endotracheal intubation or to perform screening chest roentgenogram

Fig. 3 Portable ultrasound unit that can be used at the trauma patient's bedside, in the emergency room, in order to detect free peritoneal fluid

physema. On the other hand, plain films fail in the detection of small pneumothoraces, pulmonary contusions, and lacerations. Furthermore, the specificity of supine chest X-rays is low. This is illustrated by the multiple possible origins for mediastinal enlargements, including mediastinal lipomatosis, aortic tortuosity in the elderly, and hemomediastinum originating from small arterial branches and veins, commonly associated with sternal and/or vertebral fractures. Aortic traumatic lesions account for only 15% of traumatic enlarged mediastinal shadows [17, 18, 19].

Finally, conventional radiology is used in the evaluation and characterization of limb fractures.

Ultrasonography (Fig. 3) can be easily, quickly, and safely performed in trauma patients with a small mobile ultrasound unit, which can be carried to their bedside. It has precise but limited indications. It allows detection of free peritoneal fluid, but its sensitivity in detecting hepatic, splenic, and renal trauma in the acute phase is limited [20, 21]. Ultrasonography, with transthoracic and transesophageal echocardiography, has particular applications in the identification of cardiac and aortic injuries [22, 23]; however, ultrasonography is usually suboptimal in the evaluation of severe trauma patients, with their possible chest and/or abdominal wall pains, subcutaneous emphysema, wounds, and dressings.

Angiography constitutes the gold standard in the detection of traumatic aortic and vascular injuries. Development of new interventional procedures affords alternatives to invasive surgery. Percutaneous positioning of endovascular balloon-expandable stents under angiographic guidance thus constitutes a recent and promising therapeutic tool in the management of blunt traumatic aortic injuries. Small- and mid-size artery lesions may be embolized as a substitute for or a preparation for surgery.

For the time being, MR imaging has few applications in the emergency management of blunt chest trauma. Development of rapid acquisition sequences and spreading of open magnets will perhaps allow MR to play a growing role in the ERU.

Imaging algorithms for trauma patients

Trauma patients admitted to the ER are often confused, unconscious, or even intubated. The examiner's suspicion must rely on the trauma mechanism rather than on the patients' complaints. The basic concept of trauma biomechanics is that a severe trauma usually overlaps anatomically defined areas, thus explaining, for instance, that each trauma patient shows an average of 1.5 lesions. Similarly, severe craniocerebral trauma is associated with an occult pneumothorax in 20% and with pulmonary contusions in 23%, whereas chest trauma is associated with extrathoracic injuries in up to 80% of cases [1, 24].

In agreement with others [13, 25], we propose a standardized MSCT survey (Fig. 4) as a screening test for trauma patients, based only on the trauma mechanism and its severity. Of course, this SCT survey can only be performed once the trauma patient has been hemodynamically stabilized, whereas only supine chest X-ray and abdominal echography can be performed in unstable trauma patients.

In case of significant but non-severe trauma, including traffic accidents at a speed below 50 km/h and falls from a height exceeding 1 m, we recommend to perform a cerebral MSCT, a cervical MSCT including the petrous pyramids, as well as ten incremental 5-mm CT slices on the thorax. In case of severe trauma, such as traffic accidents at a speed higher than 50 km/h, substantial car deformity, falls from a height exceeding 3 m, and/or any crush accident, cerebral MSCT should be performed, followed by cervical MSCT including the petrous pyramids as well as by thoraco-abdomino-pelvic MSCT. Cerebral MSCT affords brain evaluation, which is mandatory in unconscious or intubated patients who cannot be evaluated neurologically. Its performance in a spiral rather than an axial mode does not decrease its diagnostic value despite a small increase in artifact occurrence. Superiority of the spiral mode lies in its ability to be performed quickly, which is a major advantage in agitated patients. Cervical MSCT allows for a survey of the whole cervical spine and superior aero-digestive structures, of the petrous pyramids, and even of the skeletal face in case of clinical facial trauma (Fig. 5). The few chest-CT sections obtained in the "minimal" chest survey protocol are dedicated to the identification of occult pneumothoraces, whereas the complete thoraco-abdomino-pelvic MSCT in the "maxi-

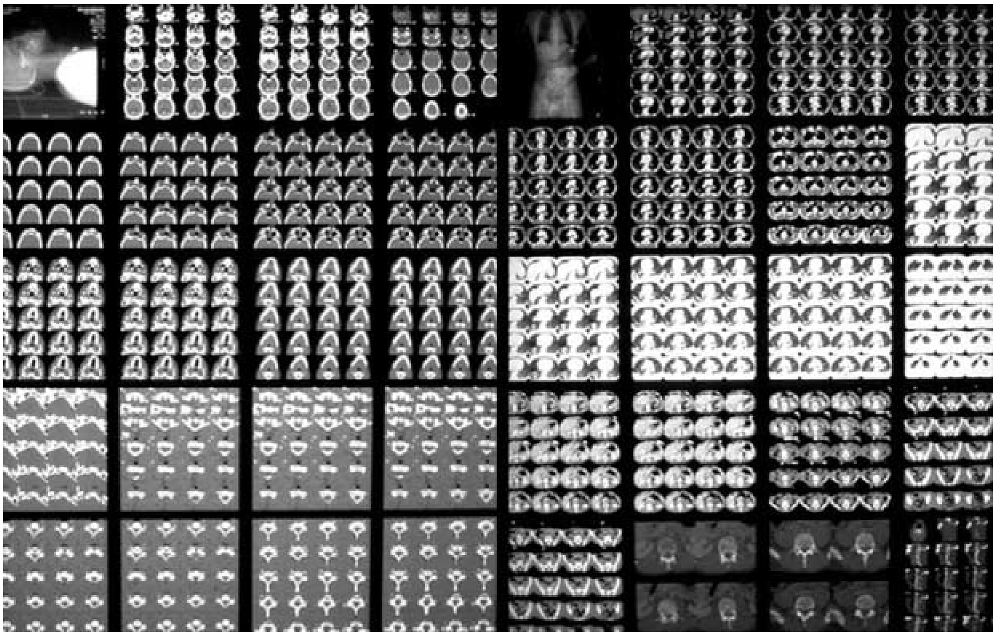

Fig. 4 Cerebral, cervical, and thoraco-abdomino-pelvic multislice CT screening survey performed in trauma patients on their admission at our institution in order to get a comprehensive and complete evaluation of the trauma patients' condition

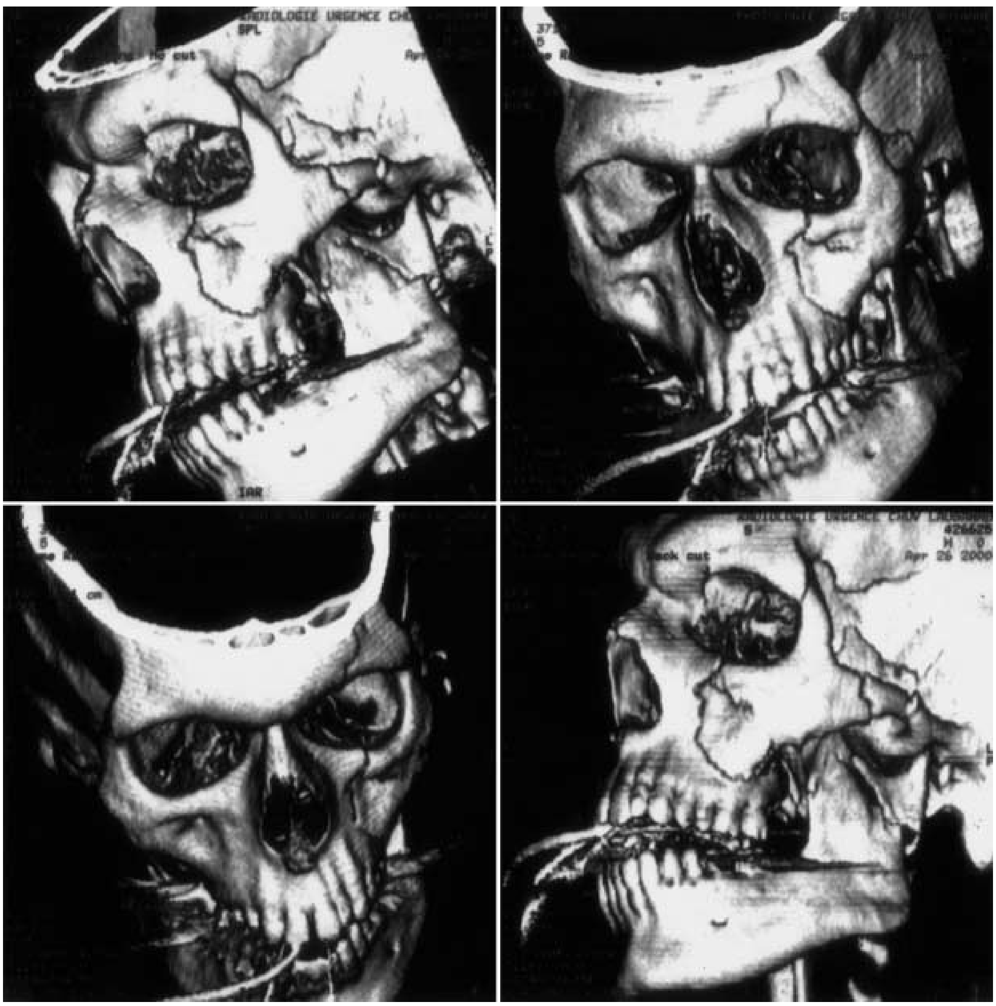

Fig. 5 Three-dimensional reconstructions of the skeletal face showing fractures of the left zygomatic tripod in an intubated trauma patient

mal" survey is designed to detect aortic lesions, which are usually clinically silent until the onset of a sudden hemodynamic decompensation. As detailed below, thoraco-abdomino-pelvic MSCT has also shown its superiority to plain films in the detection of thoracolumbar spine.

The fundamental motivation for the use of these MSCT screenings is to obtain a comprehensive and complete evaluation of the trauma patients' condition on their admission. They will indeed allow to categorize trauma patients according to the severity of their lesions, and to set up the chronology of the required therapeutic procedures. Furthermore, such screening MSCT surveys save the time wasted in moving the patients from the CT unit to the conventional radiology room or to the OR, and vice versa, when the latter present new symptoms or sudden hemodynamic instability. Finally, a comprehensive MSCT survey performed on admission affords security and confidence to the anesthetists and surgeons in charge of the trauma patients.

As every screening test, the excessive character of this MSCT survey for one single trauma patient is largely compensated by the benefit for a population of trauma patients. At our institution, we have definitely convinced our surgeons of the validity of such MSCT survey protocols, which are used on a daily basis at our ERU. They are available at our web site: http://www.hospvd.ch/public/chuv/rad/home.htm.

Multi-slice CT affords numerous advantages relating to its rapidity and its data acquisition volume; however, MSCT involves a substantially higher radiation dose to the patient than in conventional radiology [26]. Our MSCT protocols have been designed for adults of average body build. Acquisition parameters, notably kVp, must constantly be optimized, which is automatically realized by some MSCT units. Most often, they have to be lowered, especially in children, in order to reduce the effective dose. For instance, low kVp (80 kVp) can be used in children for bone evaluation such as in cervical spine surveys, affording significant dose reduction to the thyroid gland.

In addition to the radiation dose, MSCT raises several questions relating to the MSCT data volume.

The first question relates to the interpretation of MSCT examinations. The cerebral, cervical, and thoraco-abdomino-pelvic MSCT survey represents an avalanche of several hundred images, and up to 1000 images when including reconstruction with pulmonary and bone window settings (Fig. 4). The emergency radiologist has to interpret them in less than 15 min, in order of their acquisition, and under the constant pressure from consulting neurosurgeons, thoracic, abdominal, and orthopedic surgeons, each of them arguing about the priority of their field of interest over the others. Such situations may be difficult to control by training junior radiologists who have to face experienced senior consultants; therefore, a senior radiologist's efficient support is required, at least during the junior radiologist's first months in the ERU. The junior radiologists have no choice indeed but learning how to manage these uncomfortable situations very rapidly!

With respect to the MSCT data volume, hard-copy interpretation becomes irrelevant, and soft-copy interpretation on separate workstations is mandatory. Soft-copy interpretation has proved to be as reliable as hard-copy interpretation [27]. The loss of contrast due to the maximum brightness of video monitors is largely made up for by the multiple adjustment possibilities of window and level settings (Fig. 4). Soft-copy interpretation also simplifies two- and three-dimensional reconstruction processing and reading. Interpretation methods have also evolved significantly: From a slice-to-slice hard-copy interpretation, emergency radiologists, mainly junior ones, frequently adopt an organ-to-organ soft-copy interpretation. In the future, ergonomic planning of the ERU working station should start with the architectural design of the reading room, including positioning of the windows and lights, with separate computer rooms with noise shielding and air conditioning.

Multislice CT technology also questions methods of result transmission. Film printing becomes debatable, all the more when considering production and reproduction of films to maintain availability of images to multiple consulting teams. The 2D and 3D reconstructions become preponderant to summarize the imaging findings and to give a synthetic representation of the diagnosis to the intensivists and the surgical consultants.

The third question raised by MSCT technology relates to data storage. The MSCT examination printing generates a huge volume of hard copies and thus represents a high financial cost that cannot be considered in the long run. Hard-copy archiving is compelled to be replaced by picture archiving and communication systems (PACS), which constitute the companion piece for soft-copy interpretation of MSCT examinations on workstations. A typical PACS uses a hierarchical architecture with different storage media, depending on the amount and duration of storage and the expected retrieval frequency. It may easily be integrated to radiological and hospital information systems (RIS and HIS, respectively) [28, 29, 30, 31]. At our institution, when we moved from single-slice CT (SSCT) to MSCT, we observed a 400% increase in acquired data volume. As a result, our PACS central storage capacity, which had been initially evaluated at 3.7 TeraBytes on a 4-year time basis, had to be changed and increased to 21 TeraBytes, which we expect to be sufficient for the next 5–6 years.

Growing role of MSCT in ERU imaging strategies illustrated by three examples: aortic, spinal, and craniocerebral trauma

Blunt traumatic aortic injuries are a major concern in the settings of high-speed deceleration accidents, since they are associated with a very high mortality rate. Approximately 80% of patients with blunt traumatic aortic injury

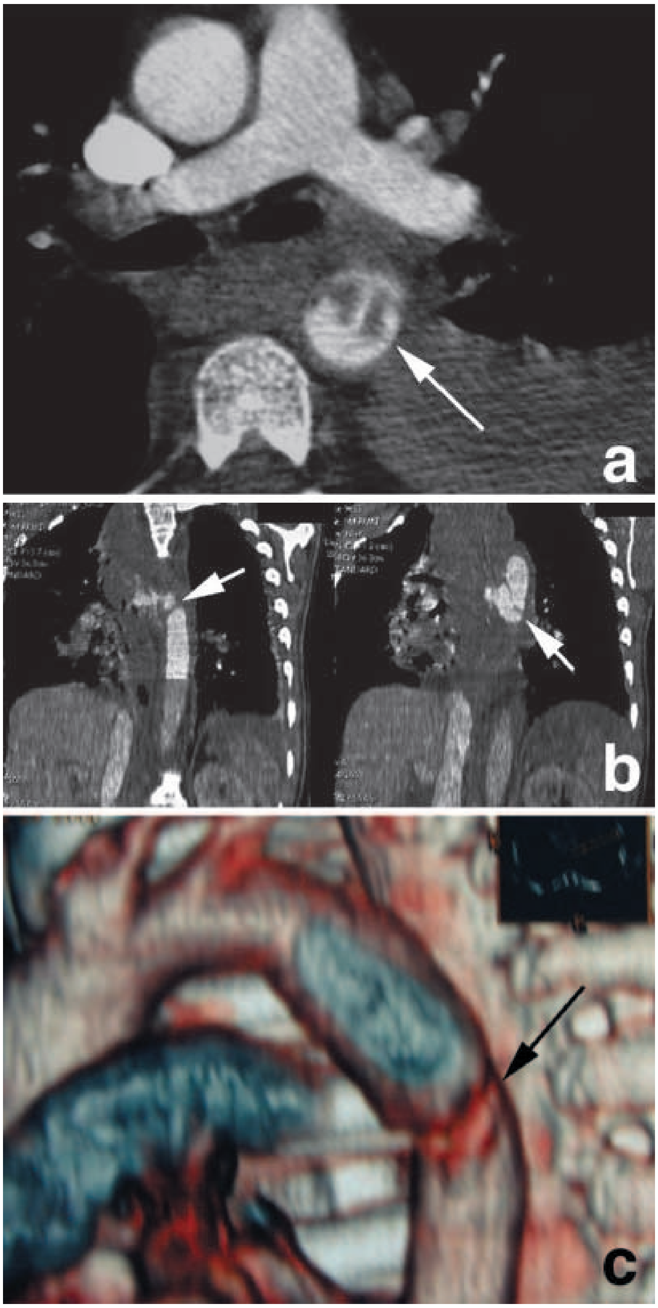

Fig. 6 **a** Blunt traumatic aortic rupture (*arrows*) at the isthmic level featuring intraluminal intimal flap, as well as hemomediastinum and left hemothorax. This example emphasizes the role of **b** two-dimensional and **c** three-dimensional reconstructions in summarizing the imaging findings and giving the anesthetists and surgical consultants a straight forward representation of the diagnosis

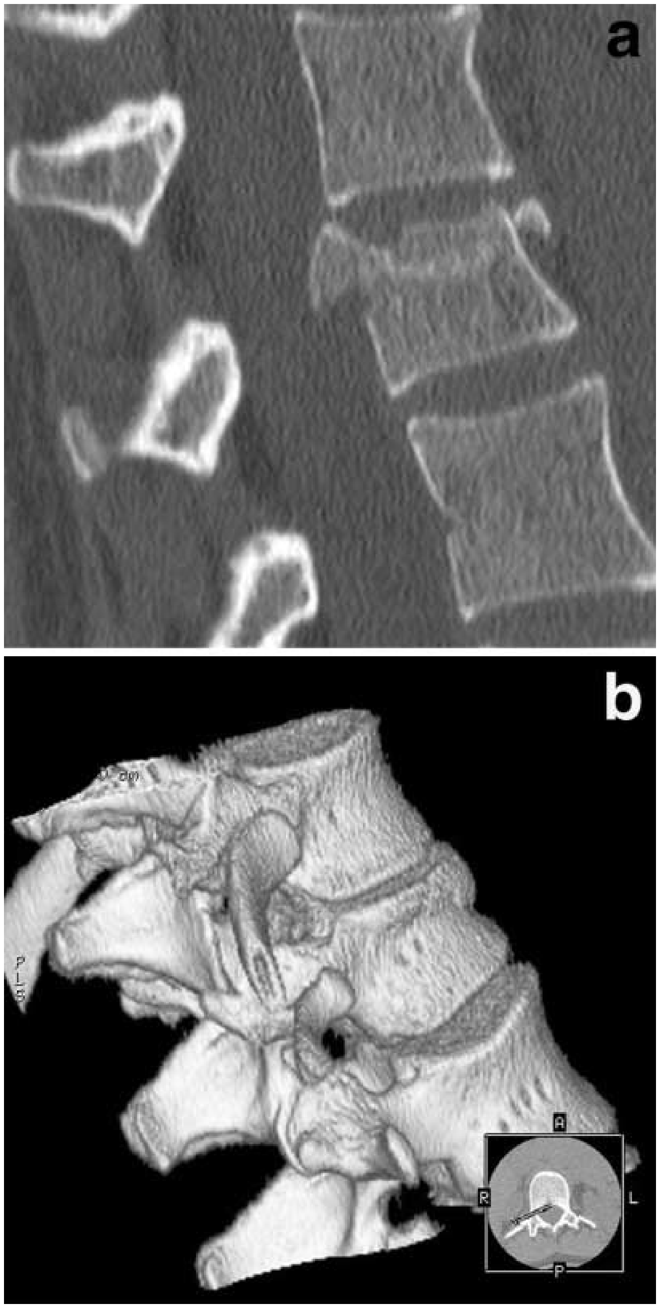

Fig. 7 **a** Multi-slice CT is highly sensitive in detecting spine fractures and in characterizing their topographic pattern and stability or instability. **b** Two-dimensional and **c** three-dimensional reconstructions are preponderant in the diagnosis

die from exsanguination at the scene of the accident. In the remaining 20%, the mortality rate of acute traumatic aortic injury in the absence of surgical treatment is also high: 30% die within 6 h, 50% within 24 h, and 90% within 4 months [32, 33]; however, with prompt diagnosis and surgery, 70% of the patients with a blunt aortic lesion who reach the hospital alive will survive [32, 34, 35, 36]. This statement challenges the emergency radiologist in his evaluation of the radiological admission survey in a severe chest trauma patient.

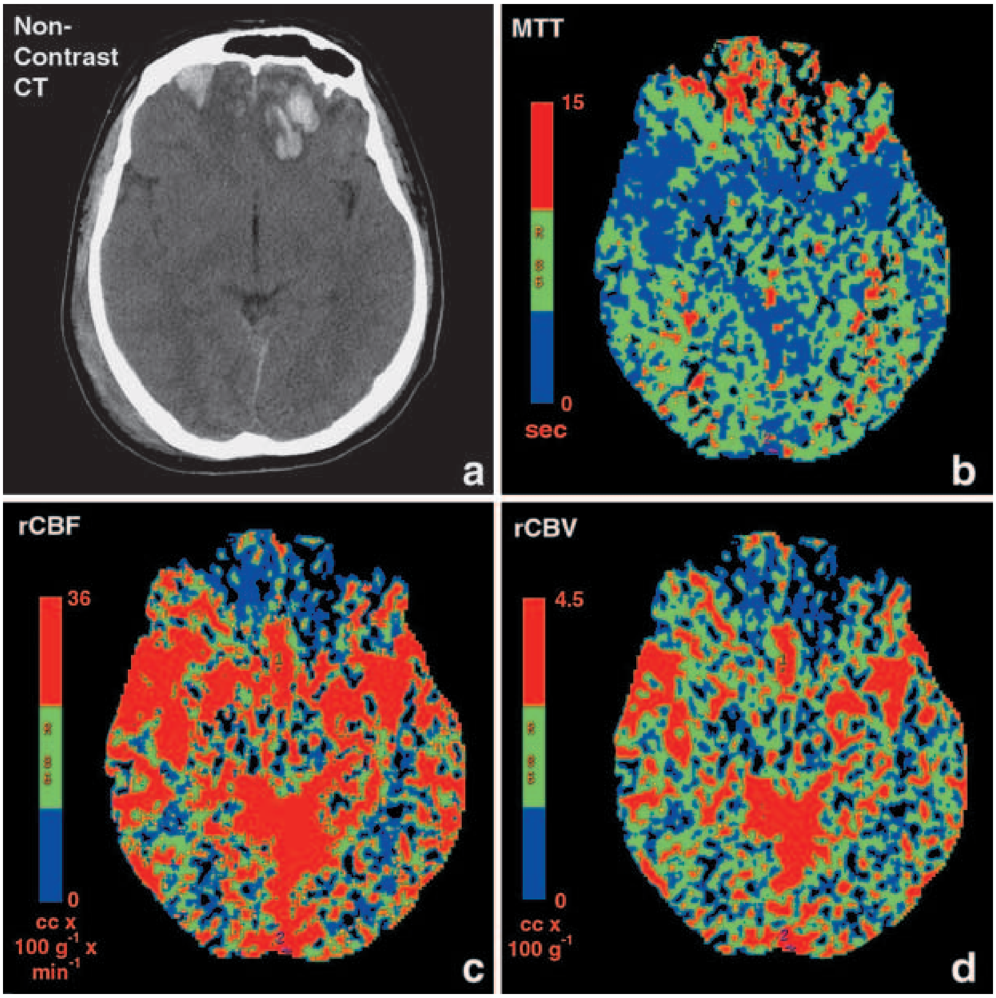

Fig. 8a–d The future of CT in the evaluation of trauma patients possibly lies in its capacity to look beyond morphologic alterations and in the evaluation of the injured organ function; thus, perfusion CT performed in craniocerebral trauma patients, for instance with hemorrhagic contusions as in this case, might afford a clinical prognosis and play a role in the guiding of associated intracranial hypertension therapeutic strategies. *rCBV* regional cerebral blood volume; *rCBF* regional cerebral blood flow; *MTT* mean transit time

With a 90% sensitivity, a 25% specificity, and a 95% negative predictive value for the identification of blunt traumatic aortic lesions, the supine chest X-ray is a worthy screening tool for mediastinal hemorrhage, but affords little as far as a definite diagnosis is concerned [17, 36, 37, 38, 39, 40, 41]. If aortography has classically been considered as the gold standard, it has a low positive response ranging to less than 15% when performed on the basis of trauma mechanism, clinical data, and chest X-ray findings [36]. Spiral CT angiography (SCTA; Fig. 6) is presently not only considered as a screening method to select patients for thoracic aortography, but also as an alternative diagnostic procedure in the identification of blunt traumatic aortic injuries, at least in hemodynamically stable trauma patients [17, 37, 38, 39]. In our series of 1050 SCTA examinations and 27 traumatic aortic injuries, SCTA demonstrated a 96.2% sensitivity, a 99.8% specificity, and a 99.7% accuracy. Hemomediastinum is an indirect sign of blunt traumatic aortic lesion, whereas direct SCTA signs of blunt traumatic aortic injuries include curvilinear intimal flap, intramural hematoma, or dissection and pseudoaneurysm. An unequivocally normal mediastinum on SCTA, with a regular aorta surrounded by normal fat and no mediastinal hematoma, has a 99.9% negative predictive value for aortic injury [37, 42].

In unstable patients, transesophageal echography plays a major diagnostic role. This semi-invasive imaging modality that yields high-resolution, real-time axial and longitudinal images of the aorta can accurately demonstrate blunt traumatic isthmic aortic lesion, with sensibility and specificity of 91% and 98%, respectively [43, 44, 45].

Another example of the superiority of MSCT in the management of trauma patients, and of the significant modifications resulting from its advent in the ERU, relates to the assessment of possible spine fractures (Fig. 7). According to yet unpublished data, we have demonstrated MSCT sensitivity to be 2.5 times that of conventional radiology in the findings of such fractures. More precisely, MSCT detects 50% additional spine fractures that are overlooked on plain films. Its sensitivity for unstable fractures is almost 100%. At our institution, severe trauma patients undergo cerebral, cervical, and thoraco-abdomino-pelvic MSCT survey for visceral injury. Dedicated axial, sagittal, and coronal reconstructions are performed on the spine, with adequate windowing, and is evaluated for possible spinal fractures. If such a fracture is diagnosed, localized plain films are obtained on the fractured vertebra in order to facilitate follow-up. If MSCT shows no spinal fracture, its diagnosis is considered as fully ruled out. No conventional radiographs are obtained in such cases, affording a substantial reduction in the duration of the evaluation of admission imaging as well as in the irradiation dose of the patients.

The future of MSCT possibly lies in functional imaging such as perfusion CT (Fig. 8) [46], which is already currently used in the management of acute stroke patients [47]. But it has also considerable impact in the evaluation of patients with craniocerebral trauma regarding their neurologic prognosis, and it might play a role in the guiding of intracranial hypertension therapeutic strategies. It does indeed afford insight into the cerebral vascular autoregulation. Perfusion CT thus represents a worthy tool in the selection of the adequate treatment in order to obtain the right average arterial pressure in the right patient. It offers individualization of the therapeutic strategy for intracranial hypertension, which had been impossible thus far.

Conclusion

Imaging, and especially MSCT, is playing a growing role in the management of trauma patients. It indeed represents the major diagnostic tool in the ER. Its use for a comprehensive assessment of trauma patients and for their categorization according to the severity of traumatic injuries will inexorably grow. This challenges the emergency radiologist, who will go to the foreground in the management of trauma patients, all the more so since development of interventional radiology will afford alternative therapeutic procedures to surgery. Trauma radiology and emergency radiology on the whole will assert themselves as consistent and thorough areas of subspecialization.

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