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CLINICAL ARTICLE - CONFERENCE REPORT

Clinical applications of intracranial pressure monitoring in traumatic brain injury

Report of the Milan consensus conference

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Abstract
Background Intracranial pressure (ICP) monitoring has been for decades a cornerstone of traumatic brain injury (TBI) management. Nevertheless, in recent years, its usefulness has been questioned in several reports. A group of neurosurgeons and neurointensivists met to openly discuss, and provide consensus on, practical applications of ICP in severe adult TBI.
Methods A consensus conference was held in Milan on October 5, 2013, putting together neurosurgeons and intensivists with recognized expertise in treatment of TBI. Four topics have been selected and addressed in pro-con presentations: 1)

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ICP indications in diffuse brain injury, 2) cerebral contusions, 3) secondary decompressive craniectomy (DC), and 4) after evacuation of intracranial traumatic hematomas. The participants were asked to elaborate on the existing published evidence (without a systematic review) and their personal clinical experience. Based on the presentations and discussions of the conference, some drafts were circulated among the attendants. After remarks and further contributions were collected, a final document was approved by the participants.

Summary and conclusions The group made the following recommendations: 1) in comatose TBI patients, in case of normal computed tomography (CT) scan, there is no indication for ICP monitoring; 2) ICP monitoring is indicated in comatose TBI patients with cerebral contusions in whom the interruption of sedation to check neurological status is dangerous and when the clinical examination is not completely reliable. The probe should be positioned on the side of the larger contusion; 3) ICP monitoring is generally recommended following a secondary DC in order to assess the effectiveness of DC in terms of ICP control and guide further therapy; 4) ICP monitoring after evacuation of an acute supratentorial intracranial hematoma should be considered for salvageable patients at increased risk of intracranial hypertension with particular perioperative features.

Keywords Traumatic brain injury · Intracranial pressure · Monitoring · Management

Introduction

For decades, ICP monitoring has been a cornerstone of TBI management. International guidelines recommend ICP monitoring not only for all salvageable severe TBI patients [Glasgow Coma Scale (GCS) score 3–8] with an abnormal CT scan, but also for a subset of patients with negative initial CT scan [5]. Indications for ICP monitoring remain debatable, with evidence rated as levels II and III. Notwithstanding, these recommendations are widely accepted, and the frequency of ICP monitoring in TBI patients is often used for assessing the level of care [40]. Over the past years the usefulness of ICP in TBI has been questioned in several reports [13, 37]. In contrast, a recent report from the New York State quality improvement program [15] suggests an association between ICP monitoring and lower mortality in TBI. These papers, based on retrospective analysis of databases, have methodological weaknesses and lead to conflicting results, leaving clinical practice relatively unaffected. Following the publication of a randomized controlled trial on two different management strategies (guided by ICP measurement or by clinical and CT data) [9] which showed no outcome differences between groups, the scientific debate restarted. In several centers the overall concept of ICP monitoring has been shaken. The study, designed by Chesnut et al. [9], compares two different management protocols, rather than ICP versus no-ICP. Even though this point is clearly stated by the authors in their original publication and in the accompanying editorial [33], more doubts on the necessity of ICP monitoring are now common. The external validity of this clinical study is questionable, with special reference to differences among the prehospital care and the extent of rehabilitation in the South American Centers where patients have been randomized. Furthermore, the statistical power of the study may be inadequate to support definitive conclusions [19].

In addition to the academic analyses and discussion, the daily management of severe TBI patients requires directions. A group of neurosurgeons and intensivists directly involved in the care of such patients met in Milan to openly discuss, and provide consensus on, practical applications of ICP monitoring in severe adult TBI.

Methods

A consensus conference was held in Milan on October 5, 2013, bringing together neurosurgeons and intensivists with recognized expertise in the treatment of TBI. The event was organized by the Italian Neurosurgical Society (SINch), sponsored by the European Association of Neurological Surgeons (EANS), and financially supported by Codman (a division of Ethicon Ltd.), with an unconditional grant. The conference started with a presentation of the BEST TRIP trial [9] by the first author (RC), who also reported on follow-up conferences and meetings. Four topics were selected and addressed in pro-con presentations focusing on indications for ICP monitoring in: 1) diffuse brain injury, 2) cerebral contusions, 3) secondary DC, and 4) after evacuation of intracranial traumatic hematomas. The participants were asked to elaborate on the existing published evidence (without a systematic review) and their

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personal clinical experience. Each presentation was followed by short questions by the audience. The participants divided into small groups, and then examined the data presented in the pro-con presentations and summarized key points to be discussed by the assembly. Based on the presentations and discussions of the conference, drafts were circulated among the attendants by two authors (FS and NS). After remarks and further contributions had been collected, a final document was approved by the participants.

Results

ICP in diffuse brain injury

Background

The Brain Trauma Foundation (BTF) guidelines [5] indicate that, in the absence of data supporting a standard treatment, there is "Level II evidence that ICP should be monitored in all salvageable patients with a GCS score of 3–8 after resuscitation and an abnormal CT scan. An abnormal CT scan of the head is one that reveals hematomas, contusions, swelling, herniation, or compressed basal cisterns. Level III evidence supports the indication of ICP monitoring in patients with severe TBI with a normal CT scan if two or more of the following features are noted at admission: age over 40 years, unilateral or bilateral motor posturing, or episodes of systolic blood pressure (BP)<90 mmHg."

Our analysis has focused on three critical points:

1) *Incidence of raised ICP (HICP) in patients with "normal" CT scan*. A study by Narayan et al. [28] identified 61 patients with a normal CT scan in whom ICP was monitored. Eight cases developed HICP, and the recommendation quoted in the guidelines is based on these eight patients. The view that comatose patients whose initial CT scan is normal or does not show a mass lesion, midline shift, or abnormal cisterns remain at substantial risk of HICP was published by O'Sullivan et al. in 1994, reporting on eight cases [30]. A more recent study by Lobato et al. [24] reported on 46 cases with completely normal admission CT scan. Patients without worsening at subsequent CT scans did not develop HICP, but one-third of cases developed new intracranial pathology with associated HICP risk. It is noteworthy that the technical capabilities of CT scanners 30 years ago were not comparable with today's standards, so that it is difficult to understand if the cases described by Narayan [28] would have been coded as "normal CT scan" if examined with better, modern equipment. Nowadays, more accurate imaging, for example, makes the detection of post-traumatic subarachnoid hemorrhage (tSAH) more frequent [12].
2) *Incidence of HICP in patients with abnormal CT scan showing diffuse damage and brain swelling*. In these patients the effacement of basal cisterns is associated with a substantially increased risk of HICP. In a paper by Toutant et al. [45] 74 % of their cases with absent cisterns developed ICP>30 mmHg. Precise ICP values in patients with diffuse TBI cannot be predicted using the Marshall CT scan classification [17], but a relationship may exist [27].
3) *Additional risk factors for HICP in patients with severe diffuse axonal injury* (DAI). Additional risk factors are related to the degree of acceleration/deceleration injury. Severe DAI may derive from high-speed, high-energy impacts, leading to multiple extracranial injuries associated with brain damage. Multiple trauma, severe hemorrhage and shock, coagulopathies, etc., may worsen the initial damage and increase the likelihood of intracranial hemorrhages, hence the probability of raised ICP.

Indications for ICP monitoring in diffuse brain injury

Comatose TBI patients are defined as patients with a GCS of 8 or less (no eye opening, not obeying commands, and not verbalizing) after hemodynamic and respiratory stabilization, and in the absence of anesthetic or paralyzing agents.

- Monitoring the ICP of comatose TBI patients with a normal initial CT is generally not recommended.
  - However, due to the occurrence of early negative CT scans which may subsequently worsen, a second CT scan is recommended. In case of further neurological worsening, the second CT scan should be performed urgently.
- Comatose patients with an initial CT scan showing minimal signs of injury (i.e. tSAH or petechiae) should be submitted to a second CT as well. Only if the initial findings worsen (e.g. contusions develop or basal cisterns become effaced) is ICP monitoring recommended, if not already implemented.
- Comatose patients with an initial CT scan demonstrating diffuse injury with signs of brain swelling (e.g. compressed/absent basal cisterns) should have ICP monitoring.

Issues to be addressed, research proposals

The mechanisms causing HICP in diffuse brain injury are not well identified. Causes of brain swelling may be different (vascular engorgement, autoregulation disturbances,

intracellular or vasogenic edema, etc.). They should be identified for potential targeted treatment, for instance through advanced imaging methods.

ICP in traumatic brain contusions

Background

Traumatic brain contusions (TBCs) can occur in up to 8.2 % of all TBI patients. The occurrence of traumatic parenchymal mass lesions can be up to 13–35 % in cases of severe TBI, representing as much as 20 % of all surgical intracranial lesions in published series [8]. The main concern in TBCs is the potential for progression to varying degrees. This evolution can be related to hemorrhagic expansion, increase of pericontusional edema, and/or appearance of new TBC in previously normal brain. Risk factors for progression are tSAH, subdural hematoma (SDH), volume over 5 cubic cm, hypotension, coagulopathy, and advanced age [20, 21, 42]. The lack of uniformity about the definition of "radiological progression", (volume change between 25 and 50 %) may account for the wide reported range of progression (from 16.4 to 51 %). In addition, a variable temporal pattern of progression is reported; this is related to an early evolution phase, within 12–24 h from injury, mainly due to hematoma expansion, and to a late phase, lasting 5–10 days after injury, due to increased pericontusional edema [2, 22, 35, 39]. Surgical indications are based on different parameters. When contusion evacuation is performed as an emergency procedure (within 24 h from injury), the main surgical indication is the radiological mass effect on admission CT scan [10]. On the contrary, when surgical evacuation is delayed, there are three main reasons for surgery: 1) increase in hematoma size and/or midline shift, 2) clinical deterioration, and/or 3) ICP increase when monitored [10, 36]. In TBC surgery, assessment of radiological and clinical signs in combination is the main determinant of any surgical decision. Serial neurologic examinations are the first and simplest form of neuromonitoring; however, they cannot be reliably accomplished in deeply comatose and/or sedated patients. Additionally, the interruption of sedation can be dangerous and difficult in patients with radiological signs of HICP, severe respiratory failure, or while undergoing emergency extracranial surgical procedures [16, 38]. When clinical monitoring is not possible, ICP monitoring may be important to detect lesion progression and to facilitate a prompt response [21, 41].

Based on the issues discussed above, the panel primarily stressed the frequency and variability of the potential for progression in TBCs. The increase of the hemorrhagic aspect of TBCs per se is not always predictive of clinical evolution, because the clinical and radiological parameters do not have the same evolutional behavior [21]. A follow-up exclusively based on sequential CT scans does not seem to be safe; ICP monitoring may help in cases at risk of further deterioration. Peterson and Chesnut [31] reported on the insertion of an intraparenchymal probe for ICP monitoring in patients with bifrontal TBCs, who are at risk of clinical progression ("talk & die patients"), even in the presence of a relatively good admission GCS score. Patients with large bifrontal TBCs are at risk of abrupt deterioration without warning due to the posterior displacement of the brain stem. In these patients, the rapid neuro-worsening could be more insidious because progressive lateralizing signs, often observed in patients with temporal uncal herniation, are absent. In a recent multicenter study of 352 patients with TBCs, the midline shift and/or the basal cisterns effacement were predictors for the onset of clinical deterioration more than hematoma evolution at follow-up CT scan [21]. In the same study, ICP was monitored after the second follow up CT scan in 45 comatose patients harboring brain contusions as the main post-traumatic lesion. In 18 patients (40 %) ICP increased to over 25 mmHg despite CSF drainage and reinforced medical therapy [41]. Sixteen of these 18 patients underwent surgical intervention (and 10 also received an associated DC) [21].

Regarding the volumetric evolution of TBCs, the panel felt that the toxic effects of contusions may be one of the reasons for the mismatches occurring between radiologic progression and ICP values, as well as between clinical deterioration and HICP. Another aspect to be considered independently of the volumetric evolution of the lesion, is brain compliance. An increase in frequency of TBI in elderly patients (often due to falls) is observed in developed countries [32]. Typically, these patients have increased brain compliance due to cerebral atrophy and can accommodate a larger volume of contusion without signs of neurological deterioration. In these elderly patients the panel concluded that HICP may not be a frequent problem. In TBI patients with focal lesions, interhemispheric supratentorial ICP gradients have been frequently described [34]. These gradients, with ICP greater on the side with the intradural lesion, are transient, disappearing with time, and may indicate an increase in the mass effect of the lesion before neurologic deterioration. The positioning of the ICP probe on the side of the larger contusion can facilitate earlier HICP detection before neurological deterioration.

Indications for ICP monitoring in TBCs

- ICP monitoring is recommended for comatose patients with TBCs in whom the interruption of sedation to check the neurological status is considered dangerous (radiological signs of HICP, severe respiratory failure, ongoing emergency extracranial surgery) or when the clinical examination is not completely reliable (severe maxillofacial trauma, spinal cord injury)
- ICP monitoring may also be indicated in comatose patients with large bifrontal TBCs and/or hemorrhagic mass

lesions close to the brainstem irrespective of the initial GCS.

Other important clinical issues are the following:

- If ICP monitoring is undertaken, the probe should be positioned on the side of the larger contusion
- There is uncertainty about the benefits of ICP monitoring in elderly patients with TBCs
- A clear distinction should be made between small millimetric petechial lesions (see previous section) and multiple contusions.
- Routine early CT follow-up is recommended to detect progression.
- Further follow-up CTs should focus on mass effect and other factors (pericontusional hypodensity, midline shift, basal cisterns effacement).
- The coagulation status and platelet count should be monitored carefully, as coagulopathy may contribute to contusion enlargement.

Issues to be addressed, research proposals

Various multimodality monitoring approaches can be considered to understand better local and global toxic effects of contusions. More studies are required to reassess the incidence of HICP, and, therefore, the value of ICP monitoring, in elderly patients with TBCs.

ICP monitoring following secondary decompressive craniectomy

Background

Primary DC refers to leaving a large part of the skull (bone flap) out after evacuating an intracranial hematoma (mass lesion) in the early phase after head injury. A DC may also be undertaken in head-injured patients who are managed in intensive care units with ICP monitoring. This is usually referred to as a secondary DC. This section is concerned with secondary DC. Many of the studies outlining the indications for ICP monitoring following severe TBI, such as that of Narayan et al. [28], were carried out when large DC was not widely used in clinical practice. Therefore, few studies have directly addressed the value of ICP monitoring and its indications after DC. When DC regained popularity (in the late 1990s and early 2000s), several studies looked specifically at ICP measurements before and after surgery. These studies generally used intractably elevated ICP (refractory to maximal medical therapy) as an indicator for DC [1, 11, 29, 43, 44]. Importantly, in almost all of these studies, ICP was monitored both before and after surgery in order to demonstrate that DC, whether bifrontal (in the case of diffuse brain swelling) or unilateral (in the case of hemispheric mass lesion), was effective in lowering ICP. Aarabi et al. [1] reported a series of 50 severe TBI patients with diffuse brain swelling; 40 patients had an HICP refractory to maximal medical therapy. These patients underwent bifrontal DC with a reduction in median ICP from 23 to 14 mmHg. Fifty-one percent achieved a good neurological outcome defined as a Glasgow Outcome Score (GOS) of 4 or 5.

Timofeev et al. [44] reported a retrospective analysis of 49 severe TBI patients, of whom 27 had ICP monitoring both before and after DC. In this series, mean ICP decreased from 25 to 16 mmHg. Favorable outcome (GOS 4–5) was achieved in 61 % of cases. The DECRA study [11] is a prospective randomized trial of early bifrontal DC vs. standard care in patients with diffuse brain swelling. All patients randomized had ICP monitoring before and after surgery. In this study, the indication for randomization to surgical intervention or barbiturates was an ICP>20 mmHg for more than 15 min (continuously or intermittently) within a 1-h period, despite first tier medical interventions. ICP was reduced substantially by DC.

None of these studies directly addresses the question of whether ICP should be monitored following DC. However, there is evidence that elevated ICP occurs even following DC [1, 29]. These studies deal almost exclusively with the clinical scenario in which DC is performed later, after ICP monitoring and failure of medical therapy (secondary DC).

Indications

These indications refer to secondary DC. Primary DC is discussed in the next section.

- ICP monitoring is generally recommended following a secondary DC in order to assess the effectiveness of DC, in terms of ICP control, and guide further therapy.

Other important clinical issues:

- If an intraparenchymal ICP probe is used, it can be inserted under direct vision intra-operatively and tunneled under the scalp. Alternatively, it can be inserted via a bolt device.

Issues to be addressed—research directions

The extent, severity, and time-course of HICP following decompressive surgery are unclear and deserve further research.

Cerebral metabolism and perfusion after decompression have been investigated in the experimental setting [47], but have not been well defined in humans.

Ethical implications, costs, and benefits of decompressive surgery after TBI are still debated and require further data. Some issues will hopefully be clarified when the results of the Rescue ICP trial, still ongoing [18], will become available.

ICP monitoring after evacuation of intracranial traumatic hematomas

Background

One of the most threatening early consequences of TBI is the development of an intracranial hematoma, which may be found in up to 45 % of severe TBI cases [6–8]. Intracranial hematomas can be extradural (EDH), subdural (SDH), intraparenchymal (ICH), or a combination thereof. The BTF guidelines for the surgical management of TBI include recommendations for the different types of hematomas regarding surgery, timing, and operative methods [6–8]. The indications are based on clinical characteristics (GCS and pupils), imaging parameters (size and mass effect), and pre-operative ICP in patients initially managed non-operatively. No specific guidance in terms of post-operative management is mentioned. Numerous large cohort studies of head-injured patients have demonstrated that HICP is independently associated with a higher risk of death following TBI [3, 4, 14]. Most of the studies looking at ICP monitoring following evacuation of intracranial hematomas concern acute SDHs. This is because approximately two-thirds of head-injured patients undergoing emergency cranial surgery (excluding ventriculostomies and insertion of ICP monitors) have an acute SDH evacuated with or without associated parenchymal injury [10]. A study by Miller et al. [26] showed that two-thirds of the 48 patients with an evacuated acute SDH had HICP in the post-operative period. Importantly, just over half of the group with HICP had uncontrollable intracranial hypertension progressing to death. In the series of Wilberger et al. [46], which included 101 comatose patients who had a craniotomy for an acute SDH, 40 % of the whole cohort had an ICP which remained below 20 mmHg in the post-operative period, while 43 % had a sustained HICP that was uncontrolled with standard therapy. The mortality rate was about 40 % in the former but close to 95 % in the latter subgroup. EDHs usually present as isolated lesions without significant parenchymal injuries/swelling. The previously mentioned study by Miller et al. [26] included 17 patients who underwent ICP monitoring after evacuation of an EDH; only two of them developed uncontrollable HICP. A study by Lobato et al. [25], which included 64 patients who underwent EDH evacuation, found that 62 % of the patients had no associated lesions or a focal brain contusion on post-operative CT scan. Mortality was 22 % in this subgroup of patients; however, mortality was 70 % in the subgroup of patients who had hemispheric swelling or multi-focal contusions on post-operative CT. In patients with post-operative ICP monitoring, one-third had well-controlled ICP (<15 mmHg), while 39 % had moderately elevated ICP (15–35 mmHg) which required further treatment. ICP was over 35 mmHg in 15 patients whose post-operative CT demonstrated hemispheric swelling, multifocal brain contusions, or diffuse brain swelling with complete collapse of the CSF spaces. The mortality rate was 73 % in this subgroup, compared to 18 % in the two subgroups whose ICP remained below 35 mmHg. The patients with HICP showed worse neurological signs (such as pupillary abnormalities and lower motor score) and higher hematoma volume. With respect to intracerebral hematomas, the series by Miller et al. [26] included 16 patients who underwent evacuation of an ICH. Fourteen patients had a mean ICP above 20 mmHg, five of whom developed uncontrollable HICP.

Overall, even though the level of available evidence is low, current clinical practice seems to accept the value of post-operative ICP monitoring in severely head-injured patients. A survey which included responses from 31 out of the 32 adult neurosurgical trauma units in the UK and Ireland found that 50 % of the centers monitor ICP in all patients after evacuation of an acute SDH. Almost all remaining centers (46 %) are in favor of monitoring patients who are not expected to be extubated soon after the operation [23].

Indications

ICP monitoring after evacuation of an acute supratentorial intracranial hematoma should be considered for salvageable patients with the following features associated with an increased risk of HICP:

- *Pre-operative* clinical findings/imaging data:
  - a GCS motor score≤5 (the risk was felt to be even higher if≤4)
  - pupillary abnormalities (anisocoria or bilateral mydriasis)
  - prolonged/severe hypoxia and/or hypotension
  - compressed or obliterated basal cisterns
  - midline shift exceeds 5 mm
  - midline shift exceeds thickness of an extra-axial clot
  - additional extra-axial hematomas, parenchymal injuries (such as contusions), or swelling
- *Intra-operative* clinical findings:
  - brain swelling

Other important clinical issues:

- Patients with associated severe extracranial injuries (severe thoracic trauma and/or requirement for multiple operative interventions) may require multiple anesthetic procedures and prolonged analgesia and sedation. In those patients, sequential neurological examination is difficult, and ICP monitoring should be considered.
- The performance of a primary decompressive craniectomy (i.e. bone flap is left out) is not a sufficient reason for not monitoring the ICP in the post-operative period if any of the above indications are present.
- Regardless of ICP monitoring, after intracranial hematoma removal, a post-operative CT should be considered.

Issues to be addressed—research directions

Prediction of HICP risk following hematoma evacuation is still uncertain. The development of a practical tool, incorporating clinical and imaging features, would be helpful for decision making.

In addition, we support the planned "Randomised Evaluation of Surgery with Craniectomy for Patients Undergoing Evacuation of Acute Subdural Haematoma"—RESCUE-ASDH trial [24] as it may clarify a crucial aspect of the optimal surgical management.

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