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CLINICAL ARTICLE - NEUROSURGICAL TECHNIQUES

Clinical and radiological findings in long-term intracranial pressure monitoring

Sebastian Antes · Christoph A. Tschan · Gerd Kunze · Lara Ewert · Anna Zimmer · Alexander Halfmann · Joachim Oertel

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Abstract
Background Advantages of telemetric devices for long-term intracranial pressure (ICP) measurement have been mentioned several times in the literature. However, descriptions of associated complications are lacking. Therefore, the presented observational study focused on clinical and radiological findings after insertion of an intraparenchymal telemetric ICP monitor.
Methods Between April 2010 and February 2013, 185 telemetric ICP catheters were implanted for diagnostic purposes. All patients were clinically followed. Radiological, microbiological and clinical data were analysed.
Results One brain abscess (0.5 %) and two cutaneous infections (1.1 %) occurred in 185 patients. *Staphylococcus* spp. could be detected in all cases. Six patients (3.2 %) suffered from single new-onset seizures and one patient (0.5 %) from a temporary hemiparesis. Intracerebral haemorrhages occurred in 15.6 %, most of the time as small punctate bleedings. Perifocal oedematous reactions surrounding inserted telemetric catheters could be observed in 46.9 %. Multiple imaging studies revealed a tendency of complete oedema resolution over time.
Conclusions Infectious as well as haemorrhagic complication rates are well comparable with the common literature. The long-term implantation of an ICP probe does not seem to increase the risk of wound infections or brain abscess formation. Surprisingly, very high numbers of oedematous reactions after insertion of the intraparenchymal ICP monitor were seen. Reasons therefore could only be speculated upon.

Keywords Intracranial pressure monitor · Telemetric ICP measurement · Telemetry · Complications · Cerebral oedema · Brain abscess

Introduction

Monitoring of intracranial pressure (ICP) is widely used in patients at risk or suspicion of intracranial hypertension [1, 4, 6]. Therefore, the insertion of intraparenchymal monitors (IPMs) or external ventricular drains (EVDs) are the most implemented procedures [1, 4, 20, 23, 24, 37]. With regard to the literature, the implantation of an IPM is thought to be a safe, effective and precise technique. Moreover, low incidence rates of haemorrhagic or infectious events constitute another advantage of this technique [1, 4, 15, 24, 28, 32]. EVDs are believed to be more frequently associated with complications, but the possibility to simultaneously monitor ICP and drain cerebrospinal fluid (CSF) is a decisive asset in several neurosurgical diseases [1, 17, 20, 24]. Descriptions of other complications as new-onset seizures or focal deficits arising from EVD or IPM insertion are rarely mentioned in the literature [5, 23, 28,

S. Antes · C. A. Tschan · L. Ewert · J. Oertel
Department of Neurosurgery, Saarland University Medical Centre, Homburg/Saar, Germany

S. Antes · C. A. Tschan · L. Ewert · A. Zimmer · A. Halfmann · J. Oertel
Saarland University Faculty of Medicine, Homburg/Saar, Germany

G. Kunze
Raumedic AG, Helmbrechts, Germany

A. Zimmer
Department of Diagnostic and Interventional Neuroradiology, Saarland University Medical Centre, Homburg/Saar, Germany

A. Halfmann
Institute and State Laboratory of Medical Microbiology and Hygiene, Saarland University Medical Centre, Homburg/Saar, Germany

J. Oertel (✉)
Klinik für Neurochirurgie, Universitätsklinikum des Saarlandes, Kirrberger Straße, Gebäude 90.5, 66421 Homburg, Germany
e-mail: joachim.oertel@uks.eu

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34, 35, 37]. More so, explicit studies focusing on abnormal findings in tomographic imaging series do not exist so far. Presumably the fact that IPMs or EVDs just stay inserted for a few days can explain the missing information.

However, long-term ICP monitoring over weeks or months is frequently required in many clinical situations. A promising solution to meet the requirement has been the development of "wireless" ICP measurement probes [2, 7, 9, 12, 16, 19, 25, 30, 39, 40]. So-called "telemetric devices" are designed to permanently remain under the sutured skin. Associated advantages have been mentioned several times in the literature whereas periprocedural complications are rarely described [7, 16, 19, 25].

The presented retrospective observational study particularly focuses on uncommon findings in the clinical course of patients who had undergone insertion of an intraparenchymal telemetric ICP measurement device. Moreover, clinical data were compared with radiological and microbiological findings.

Materials and methods

Patients

Between the 23rd of April 2010 and the 22nd of February 2013, 185 intraparenchymal telemetric ICP measurement probes have been inserted in the frontal lobe of patients with suspected (n=111) or known (n=74) hydrocephalus. Indications for using the telemetry as part of the diagnostic work-up were suspected normal-pressure hydrocephalus (n=68), occlusive hydrocephalus (n=27), benign intracranial hypertension (n=6) or ICP elevation for other reasons such as Chiari malformation or craniosynostosis (n=10). In already shunt-treated patients, the P-tel probe was applied to exclude shunt dysfunction (n=30) or CSF overdrainage (n=25). The other 19 telemetry catheters were inserted parallel to first-time shunt implantations (n=6) or endoscopic third ventriculostomies (ETV) (n=13) to monitor the postoperative course.

The patient cohort consisted of 95 females (51.4 %) and 90 males (48.6 %). Mean age at the time of catheter implantation was 54.9±23.0 years (range, 1–91 years). On the 22nd of February 2013, 158 of 185 P-tel probes were already explanted. Related implantation periods ranged from 3 to 409 days (mean, 60.7±58.1 days). At the time of preparation of this work, 27 P-tel probes were still implanted.

The telemetric device

The device (Neurovent P-tel; Raumedic, Helmbrechts, Germany) consists of a round ceramic housing (diameter, 31.5 mm; height, 4.3 mm) embedding the microchip for telemetric data transmission. The housing is connected to a parenchymal polyurethane catheter (length, 30 mm; diameter, 5 French) with a pressure transducer at the distal end (Fig. 1). The pressure transducer contains several electrical resistors doped on a flexible membrane that is in contact with the pulsating brain tissue. An increase in ICP leads to a stretching of this membrane, affecting the length of the doped resistors and consecutively the value of the electrical resistance of the system. To activate and start ICP measurement, a special external reader unit (Reader TDT1 readP; Raumedic), supplying the passive device with energy, has to be placed over the intact scalp wound. Data transmission through the skin and even through a plaster is accomplished by RFID-technique (radiofrequency identification). The P-tel microchip modifies an oscillating electromagnetic field—generated by the TDT1 readP—with repetitive short-circuits (load-modulation). The reader-unit that is connected to an external monitor finally registers ICP dependent modification of tuned circuit. ICP values can be detected with a frequency of 1 or 5 Hz and can be displayed and stored on the external monitor.

Technique of surgical insertion

All P-tel implantations were performed in accordance with the hospital's standard (Department of Neurosurgery, Saarland University Medical Centre and Saarland University Faculty of Medicine, Homburg, Germany). A 10-mm burr hole was drilled 1-2 cm anterior to the coronal suture and about 3 cm lateral to the midline. Most implantations were done on the left hemisphere. Deviations only occurred in cases of anatomical particularities, in the presence of a left-sided cerebral

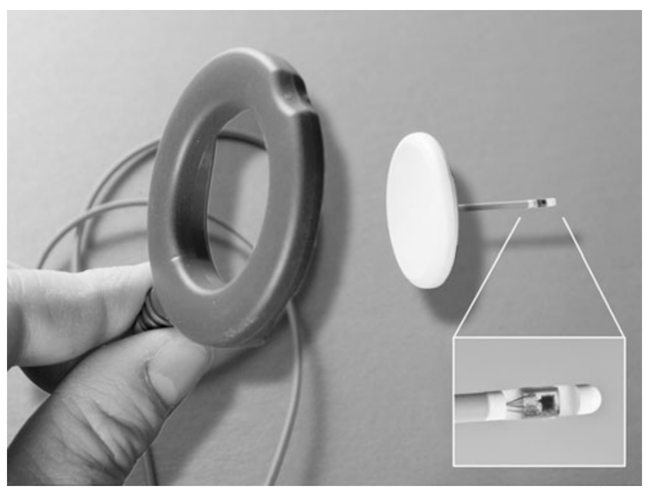

Fig. 1 *Right side*: Telemetric ICP measurement device (Raumedic Neurovent-P-tel). Pressure transducer (see enlargement) is located at the distal end of the parenchymal catheter. The round ceramic housing remains on the skull surface under the sutured skin after implantation. *Left side*: Special reader unit (Raumedic Reader TDT1 readP), which supplies the passive telemetric device with energy, has to be placed over the implant. Consecutively, a cable-free connection for ICP data transmission can be established

shunt or in cases of parallel endoscopic procedures (see below). After coagulation and cruciform opening of the dura and pia mater, the distal part of the polyurethane catheter was carefully advanced through the frontal brain parenchyma. The round housing of the telemetric device remained directly on the skull surface. Wound closure followed. Normally, the whole procedure took between 10 and 20 min.

In ten patients, who have been treated by ETV, the P-tel catheter was inserted into the puncture channel of the endoscopic approach.

Clinical complications

Ambulatory as well as stationary medical files of all 185 patients were retrospectively evaluated. Personal communications between patients and colleagues (e.g. via phone call, e-mail, letter post, etc.) were not considered. Special focus was on perioperative and postoperative complications such as new-onset seizures, wound healing disorders, brain abscesses and new focal deficits. All concomitant circumstances were also collected (e.g. shunt implantation and subsequent infection).

Microbiological examinations

CSF samples were taken in 75 patients (e.g. during lumbar puncture or shunt-implantation). In 51 patients, microbiological wound swabs of the puncture channel of the catheter were collected during probe explantation. CSF specimens were grown both on solid (blood, chocolate, and MacConkey agar) and in liquid (brain heart infusion broth) media for 72 h, while swabs were plated on blood and MacConkey agar, and held for 48 h. Species identification of cultured microorganisms was achieved using MALDI-TOF (Bruker Daltonics, Bremen, Germany).

Imaging studies

One hundred and sixty of 185 patients received a total of 470 computed and/or magnetic resonance tomographies (CT and/or MRI) during the postoperative course. This corresponds to an average of 2.94 imaging studies per patient (range, 1–14). Figure 2 shows an overview of all executed imaging studies. Particular attention in the evaluation of all images was paid on the following points:

- Cerebral oedema:

  Localised homogenous and partly finger-shaped hypodensities in CT images, respectively hyperintensities in T2-weighted or FLAIR-weighted MRI images, were defined as “cerebral oedema”. If such oedematous alterations occurred in the surrounding area of the inserted P-tel catheter, the maximum two-dimensional extension was calculated (in an axial slice) according to the formula: length × width (mm^2). Related areas were categorised as follows:

  1. Minimal oedema: area<150 mm^2
  2. Small oedema: area<600 mm^2
  3. Medium-size oedema: area<1,100 mm^2
  4. Large oedema: area>1,100 mm^2

  An illustrative example showing a “large” perifocal oedema is given in Fig. 3.

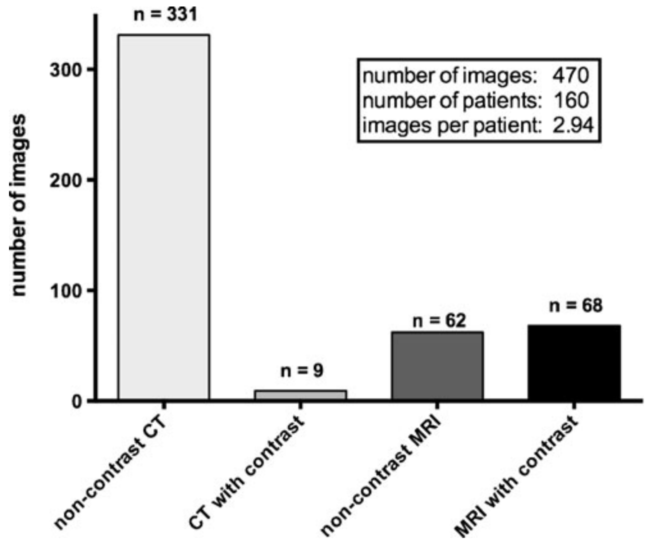

Fig. 2 The distribution of different imaging techniques that have been performed during the postoperative course

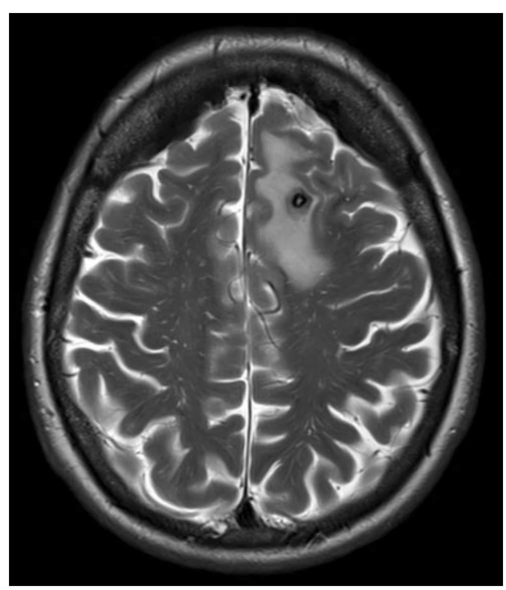

Fig. 3 Illustrative example of a “large” oedema surrounding the P-tel catheter in a T2-weighted MRI study

- Haemorrhages:

Haemorrhages were classified according to the grading system proposed by Blaha et al. in 2003 [5]:

1. Grade I haemorrhage: small punctate haemorrhages, no focal deficits
2. Grade II haemorrhage: larger bleeds, no focal deficits
3. Grade III haemorrhage: larger bleeds with associated focal deficits

An illustrative example showing grade I and grade III haemorrhages is given in Fig. 4.

- Contrast enhancements:

A distinction is made between slight contrast enhancements of the puncture channel and suspicious ring enhancing lesions with surrounding oedema (suspected brain abscess).

An illustrative example showing suspicious contrast enhancements is given in Fig. 5.

Results

Clinical efficiency

The application of the probe as part of the primary diagnostic work-up in suspected ICP disorders resulted in further therapeutic measures (shunt implantations or endoscopic procedures) in 90 of 111 patients (81 %). Suspected shunt dysfunctions or CSF overdrainages could be verified by telemetric ICP measurements in 77 % and 96 % respectively. Therapeutic consequences have been surgical shunt (or valve) revisions as well as gravitational valve insertions. In more than 77 % of all newly shunt-treated patients (62 of 80 patients), one or more postoperative valve adjustments were executed under telemetric monitoring to optimise the clinical outcome. Twenty-nine patients were treated by ETV. Periodical postoperative ICP measurements enabled an early differentiation between ETV responders (n=24) and non-responders (n=5). A graphical overview summarising indications, measuring results and therapeutic consequences is provided in Fig. 6.

Due to clinical complications (see below), premature and unplanned explantations of the probe were executed in eight patients. In six of them, the telemetric ICP measurements performed prior to the complication incident were sufficient enough to reach adequate therapeutic decisions.

Clinical complications

The overall complication rate after implantation of the Raumedic Neurovent P-tel probe in this observational study was 5.9 % (in 11 of 185 patients). Three clinical infections were observed, including one brain abscess and two superficial wound infections. Six patients suffered from single new-onset seizures (four generalised and two complex-partial) in the postoperative course. A temporary hemiparesis was seen in one patient due to an intracerebral haemorrhage surrounding the catheter. Another patient showed a prolonged reduction of the general condition with exhaustion and weakness. An infection, seizure or an intracerebral bleeding may not be evidenced.

Detailed epicrises of these patients, associated radiological and microbiological findings as well as subsequent therapeutic measures are described at the end of this chapter. Additionally, Table 1 offers all relevant clinical complications that can be associated to the P-tel insertion.

Microbiological findings

CSF samples were taken from 75 different patients during the postoperative course after P-tel insertion. Bacterial growth

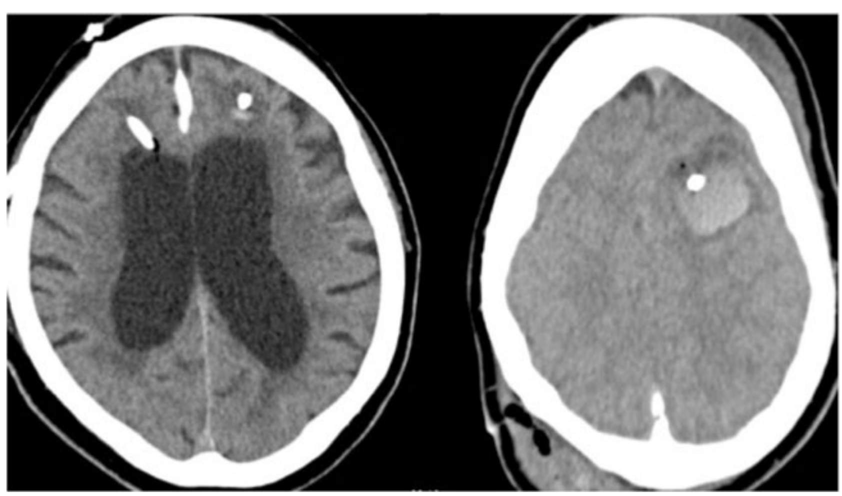

Fig. 4 Grade I (*left side*) and grade III (*right side*) haemorrhage after P-tel insertion. The patient with the grade III haemorrhage suffered from temporary hemiparesis

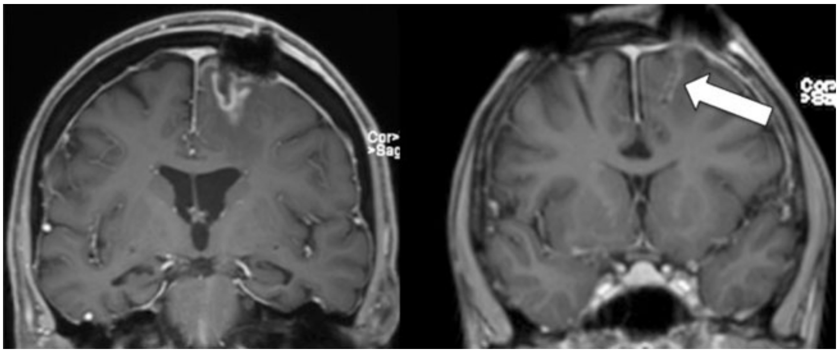

Fig. 5 *Left side*: Contrast-enhanced T1-weighted MRI shows brain abscess formation surrounding the inserted P-tel catheter. Microbiological examination after surgical removal could identify growth of *Staphylococcus capitis*. *Right side*: Slight contrast enhancement along the P-tel catheter (*white arrow*). The intraoperative wound swab of the puncture channel was free from any bacterial colonisation

could be detected in two cases (one *Enterococcus faecalis* and one *Staphylococcus epidermidis*).

Intraoperative wound swabs were taken from 51 patients during explantation of the telemetric probe. In 41 of 51 cases (80.4 %), microbial cultures remained sterile, while growth was monitored in swab cultures of the remaining ten patients (*Staphylococcus epidermidis* in four cases, *Staphylococcus capitis* in four cases, *Propionibacterium acnes* in one case and *Micrococcus luteus* in one case).

Imaging studies

Seventy-five of 160 patients (46.9 %) showed oedematous reactions in the postoperative imaging studies. In nine patients (12 %), a large oedema could be detected in the region of the inserted P-tel catheter, whereas the majority of the patients presented with small (45.3 %) or medium-sized alterations (33.3 %) (Fig. 7). Due to multiple imaging studies during the postoperative period, a complete resolution of the oedematous reactions could be found in 48 patients. At the time of oedema resolution, 24 catheters were already explanted, and 24 catheters were still in situ. The other 27 patients showed oedematous reactions in their last imaging study, but more than 50 % of this group only received one postoperative CT or MRI so far. Additionally, 22 of these 27 patients (81.5 %) were still equipped with the telemetric device at the time of preparation of this manuscript.

Eighty patients were treated by first-time shunt implantation either parallel (n=6) to the P-tel insertion or at later time (n=74). Imaging studies of 11 patients of this group could followed. In 62 of all newly shunt-treated patients (n=80, both groups), one or more postoperative shunt valve adjustments were performed under telemetric ICP control to optimise the clinical outcome. In group B, suspected shunt dysfunctions were verified in 23 of 30 cases (77 %). In 24 of 25 patients, CSF overdrainage could be confirmed (96 %). Consequences were shunt (or valve) revision surgeries (n=23) respectively gravitational valve insertions (n=24). Considering the patients from group A and B, a total of 29 patients were treated by ETV. In these patients, the postoperative course was monitored by performing periodical ICP measurements. In five of 29 cases, telemetry was helpful for early identification of ETV non-responders

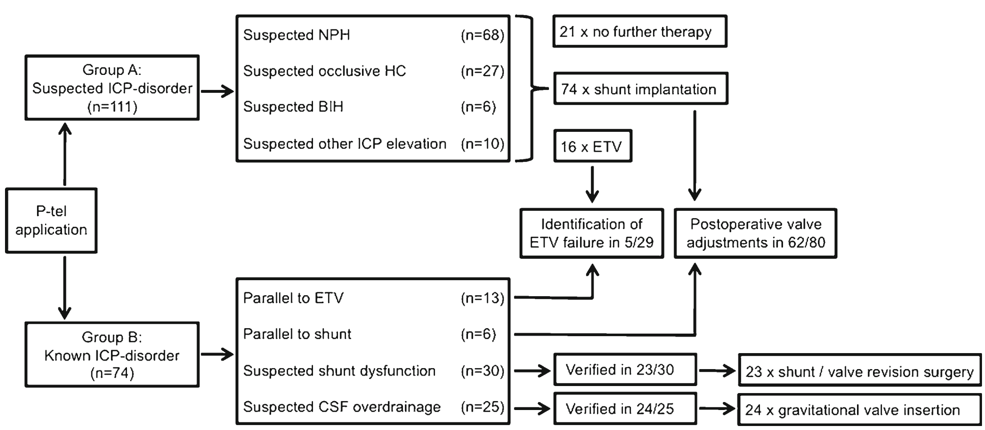

Fig. 6 The P-tel probe was applied in 111 patients with suspected ICP disorders (group A) as part of the primary diagnostic work-up. Suspected diagnoses were normal-pressure hydrocephalus (n=68), occlusive hydrocephalus (n=27), benign intracranial hypertension (n=6) or ICP elevation for other reasons (n=10). In 74 patients with an already known hydrocephalus (group B), the telemetric device was inserted to exclude shunt dysfunction (n=30) or CSF overdrainage (n=25). The other 19 telemetric catheters were inserted parallel to first-time shunt implantation (n=6) or ETV (n=13) to monitor the postoperative course. In group A, telemetric ICP measurements resulted in 74 cases in shunt implantations and in 16 cases in ETVs. In the other 21 patients, long-term ICP measurements did not reveal significant pathologies; consecutively no further surgery

Table 1 Clinical complications associated with the P-tel implantation (*n* =185) and summary of the literature review

	Incidence (study)	Study (literature)	Incidence (literature)
Brain abscess	0.5 %	Morton et al. 2012 [28]	Case report
Cutaneous infection	1.1 %	Poca et al. 2002 [31]	2.2 %
		Shapiro et al. 1996 [35]	0.4 %
Meningitis/ ventriculitis	0.0 %	Gelabert-G. et al. 2006 [15]	0.0 %
		Martinez-M. et al. 2000 [26]	2.9 %
		Kroin et al. 2000 [25]	25.0 %[a]
New-onset seizure	3.2 %	Wang et al. 2013 [37]	4.4 %[b]
New focal deficit	0.5 %	Anderson et al. 2004 [1]	0.0 %
		Blaha et al. 2003 [5]	0.2 %

[a] Animal experiment with four dogs

[b] Study with 45 patients suffering from acute intracerebral haemorrhage

Fig. 8 P-tel tip located in the ipsilateral frontal horn due to extreme dilatation of the ventricular system. In all of these cases (*n*=12), no oedematous alterations could be observed

reveal an analogous oedematous reaction in the surrounding area of the new inserted ventricular catheter. This corresponds to an incidence of 13.8 %.

Due to abnormal ventricular dilatation in 12 patients (Fig. 8), the tip of the parenchymal catheter was found located in the ipsilateral frontal horn. None of these patients presented with perifocal oedema. In another ten cases, the P-tel probe was inserted in the endoscopic approach after performing ETV. Also these patients were free from any oedematous reaction.

With regard to catheter-associated haemorrhages, an overall incidence including punctate as well as larger bleedings of 15.6 % can be calculated (25 of 160 cases). According to the introduced grading scale, 15 of these were grade I (9.4 %), nine were grade II (5.6 %) and one was grade III (0.6 %) without necessity for surgical haematoma removal.

Four of the 80 patients with first-time shunt implantations showed either grade I haemorrhages (*n*=2) or grade II haemorrhages (*n*=2). Total incidence of intracerebral haemorrhage after shunt implantation in this observational study was 5.0 %.

Seventy-seven of all 470 imaging studies (*see* Fig. 2) were enhanced by intravenous injection of contrast agent. Eighteen patients presented slight enhancements along the puncture channel of the P-tel catheter. A ring enhancement indicating possible brain abscess formation was seen in four patients.

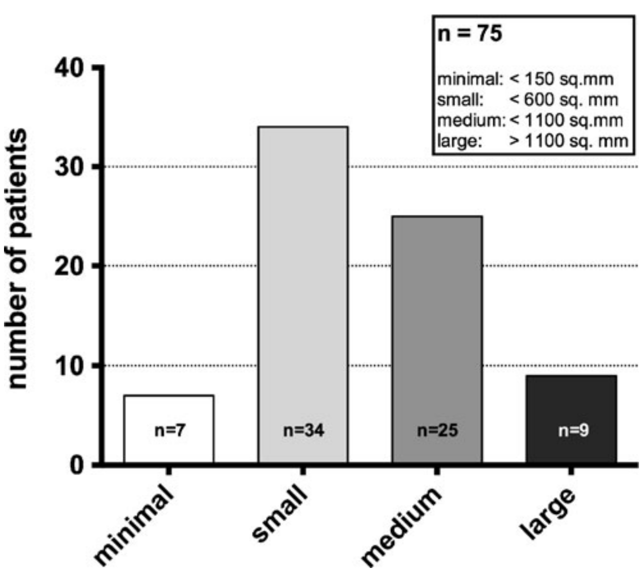

Fig. 7 The distribution of oedema sizes in the 75 patients concerned. Most oedematous reactions were small-sized (45.3 %)

Table 2 Specific findings in imaging studies after P-tel implantation (imaging studies of 160 patients available) and comparison with the literature

	Incidence (study)	Study (literature)	Incidence (literature)
Perifocal oedema	46.9 %	Englot et al. 2011 [10]	32.4 %[a]
		Ryu et al. 2004 [33]	39.0 %[a]
		Weise et al. 2010 [38]	6.3 %[a]
Haemorrhage	15.6 %	Anderson et al. 2004 [1]	6.4 %
		Blaha et al. 2003 [5]	9.7 %
		Guyot et al. 1998 [17]	2.8 %
		Kasotakis et al. 2012 [24]	0.6 %
Slight contrast enhancement	23.4 %	n.a.	n.a.
Ring enhancing lesion	5.2 %[b]	n.a.	n.a.

[a] Cerebral oedema surrounding deep brain stimulation leads

[b] Bacterial growth in one of four cases

All morphological abnormalities in imaging studies and the related incidences are clearly summarised in Table 2.

Association between clinical, radiological and microbiological findings

To ensure overview, patients were divided into different groups depending on the clinical findings and related oedematous reactions in the imaging studies (160 patients). Twenty-five patients had no postoperative imaging so far. With regard to the ambulatory and stationary medical files no clinical complications occurred.

- Group I: oedematous reactions, no clinical complications (*n*=62)
- Group II: oedematous reactions and associated complications (*n*=8)
- Group III: oedematous reactions plus non-associated complications (*n*=5)
- Group IV: no oedematous reactions (*n*=85)

Group I

With regard to the relatively high percentage of oedematous reactions seen in CT and/or MRI (total incidence, 46.9 %), it can be stated that the majority of the patients did not suffer from any oedema-associated clinical complication.

One patient of this group showed a ring-enhancing lesion with a medium-sized surrounding oedema. Clinically, he was free from headaches, seizures, fever, etc. Microbiological findings were not available in this case. Further imaging studies (CTs and MRIs) revealed complete disappearance of suspicious morphological alterations.

CSF samples were taken in 31 patients; bacterial growth appeared in one case (Staphylococcus epidermidis). Fourteen of 15 wound swabs remained sterile, while one swab revealed bacterial growth (*Staphylococcus capitis*). Neither the patient with the positive CSF culture nor the patient with the positive wound swab showed any clinical abnormality; and given the commensal nature of the recovered specimen, both were therefore regarded as contaminants.

Group II

A total of eight patients with oedematous reactions suffered from catheter-associated complications.

One patient presented with ring-enhancing cerebral abscess located in the region of the implanted catheter. Surgical removal of the catheter and the abscess was executed; microbiological examination revealed growth of *Staphylococcus capitis*. A triple antibiotic combination including *metronidazole*, *meropenem* and *rifampicin* was applied for 4 weeks. Thereafter, the postoperative course was satisfactory with a complete clinical reconvalescence.

Another patient with a suspicious enhancing lesion showed a reduced physical condition. Brain abscess with bacterial colonisation could not be verified by intraoperative wound swab. Clinical improvement was achieved 3 months after P-tel explantation. Moreover, subsequent imaging studies showed complete resolution of previously diagnosed abnormality.

Two patients presented with disorders of wound healing over the implanted devices. *Staphylococcus epidermidis* was detected in both cases. Imaging studies did not show any signs of brain abscess formation. A CSF sample was additionally taken in one patient but bacterial growth could not be evidenced. Wound healing was sufficient after P-tel explantation in both cases.

New-onset seizures occurred in four patients (three generalised and one complex partial). All patients presented with medium-sized oedema and slight contrast enhancement along the puncture channel of the catheter. Three of four microbiological examinations were inconspicuous; *Staphylococcus epidermidis* was seen in one case (wound swab). All P-tel catheters were immediately explanted after the primary event. Three patients were temporarily treated (range, 4 weeks to 7 months) with anticonvulsants (*levetiracetam*). Recurrent events could not be observed.

Group III

Five patients with oedematous alterations in MRI or CT suffered from clinical complications that can retrospectively not be associated with the P-tel insertion.

Prolonged hospital stays with reduced physical conditions occurred in one case due to early shunt infection (positive CSF culture with *Enterococcus faecalis*) and in four cases due to further surgical procedures (one endoscopic fenestration of arachnoid cyst and three transition syndromes after shunt implantation or CSF infusion study). The one patient with the proven shunt infection also showed a ring enhancing lesion in the surrounding area of the previously inserted P-tel probe. But clinical deterioration occurred 2 weeks after shunt implantation when the P-tel probe had been already explanted for more than 5 weeks.

Group IV

A total of 85 patients (53.1 %) showed no oedematous alterations in the imaging studies. Seventy-five patients were completely free from any clinical complication. In five patients of this group (5/75) asymptomatic bacterial growth could be detected during P-tel explantation (two *Staphylococcus capitis*, one *Staphylococcus epidermidis*, one *Propionibacterium acnes* and one *Micrococcus luteus*).

Complicated postoperative courses in three of the symptomatic ten patients can be attributed to the P-tel insertion.

Two patients suffered from new-onset seizures (one generalised and one complex partial) and one patient from a temporary hemiparesis after grade III haemorrhage. The seizures were temporarily treated with *levetiracetam* for 3 months (partial) respectively 6 months (generalised). No further seizures happened.

Discussion

The findings and consecutive interpretations are based on retrospective analyses of medical files, imaging studies and documented laboratory analyses. It should be considered that the methodology of data evaluation as described in the "Materials and methods" section could bias the results.

The overall clinical complication rate of the Raumedic telemetry catheter in this series with 185 patients was 5.9 %. In 11 of 185 patients, the postoperative course was complicated due to brain abscess formation in one case, superficial wound infection in two cases, single new-onset seizure in six cases, temporary hemiparesis in one case and prolonged physical reconvalescence after P-tel insertion in one case. With regard to the microbiological examinations, only two of the 75 CSF samples showed evidence of microbial pathogens. One patient with a positive culture was clinically asymptomatic, the other one presented with a shunt-infection (not associated with the P-tel probe). Forty-one of the intraoperative wound swabs (n=51) were completely free from any bacterial colonisation. *Staphylococcus* spp. was detected in the brain abscess formation, in two superficial wound infections and in one patient suffering from a new-onset seizure. Thus, six colonised swabs were asymptomatic. Perifocal oedema surrounding the P-tel catheter was detected in 75 of 160 patients (46.9 %). By taking the clinical course into account it can be stated that 89.3 % of all oedematous reactions were not associated with clinical complications.

Infection rates in the literature

The literature dealing with telemetric devices is mostly focused on technical principles, measuring accuracy, catheter stability or surgical techniques for insertion [2, 7, 9, 12, 16, 19, 25, 30, 39, 40]. Complications were mostly not even mentioned [2, 8, 9, 13, 27, 29, 30]. Gücer et al. [16] used epidural catheters in 127 patients, whereas Heppner et al. [19] inserted a total of six subdural probes. Both study groups could not detect any infectious complication. Unfortunately, information about results of imaging studies or microbiological examinations was not provided. Kroin et al. [25] performed an animal experiment with intraparenchymal telemetric devices. One of the four dogs became lethargic some weeks after catheter insertion, leading to the decision to kill the animal. Histopathological examination of the brain could reveal signs of fulminant meningitis and ventriculitis. However, direct comparisons to the presented study should be done carefully due to different types of catheters (epidural and subdural) or due to the application in animals.

The incidence of infectious complications in the presented study is low (0.5 % for brain abscess and 1.1 % for wound healing disorders). Nevertheless, several works in the past have never associated IPMs with meningitis or cerebral abscess [1, 4, 15, 22, 28]. For example, a large series using the Camino ICP device stated no clinically relevant infection in a series with 1,000 patients [15]. The first case-report referring to an IPM associated cerebral abscess with evidence of *Staphylococcus aureus* was published in 2011 [28]. But concomitant circumstances presumably played a significant role in that case. The young patient suffered from severe traumatic brain injury with related bifrontal skull fracture and underlying intracerebral contusion. Additionally, a second IPM was (re-)inserted through the same approach a few days later, and the child was treated with dexamethasone over several days (due to airway oedema).

Regarding only superficial wound infections, Shapiro et al. [35] observed one case after IPM insertion in 244 patients. Three cutaneous infections were seen in a series with 137 IPMs by Poca et al. [31].

In the present study, CSF cultures and microbiological examinations of the puncture channel could detect growth of microbial pathogens in 12 of 126 cases. Only four of them can be associated with clinical complications arising from P-tel implantation. *Staphylococcus* spp. were responsible for wound healing disorders in two cases, brain abscess in one case and presumably for a new-onset seizure in another case.

The bacterial colonisation of catheter tips is a well-known phenomenon. Incidences of asymptomatic culture-positive IPMs range from 8.5 to 17.0 % [4, 15, 26, 31]. Maybe the fact that IPMs usually remain just a few days in situ can explain the phenomenon of very rare infection rates. In cases of inserted telemetric devices, the contact time between brain tissue and the catheter is significantly longer. Thus, the long-term implantation of the telemetric device could increase the probability of bacterial growth and infectious complications.

Haemorrhages and seizures

A total of six patients (3.2 %) suffered from new-onset seizures in the postoperative course. Four of them showed oedematous reactions in the imaging, the two others not. Associations between new-onset seizures and implanted IPMs or EVDs have been not described in the literature. It should, however, be considered that most IPMs are used in clinical routine in cases of traumatic brain injuries or cerebral bleedings [4, 23, 37]. Occurring epileptic events will not be attributed to IPM insertions but rather to the traumatic or bleeding incidents [3, 36, 37].

One patient in this study suffered from temporary hemiparesis due to intracerebral haemorrhage (grade III) after P-tel implantation (Fig. 4). The overall incidence of haemorrhagic complications including punctate as well as larger bleeds was 15.6 %. Fortunately, most observed bleedings were asymptomatic (24/25) or even very small (15/25). In general, the insertion of an IPM is believed to be a safe method with low haemorrhagic complication rates between 0 and 10 % [1, 17, 22, 24, 26]. By subsuming P-tel associated grade II and grade III haemorrhages (incidence: 6.2 %), the findings are well comparable with those described in the literature.

Asymptomatic bleedings also occurred after ventricular catheter implantation during first-time shunting in four of 80 cases (5.0 %). This rate is consistent with recently published data [24]. Overall, the occurrence of haemorrhages after shunt or EVD insertion has been described as high as 17.6 % [1].

Radiological findings

The appearance of oedematous alterations in imaging after implantation of an intracranial ICP catheter has not yet been described in the literature. With regard to the dimensions of the telemetric catheter (diameter, 5 French; total length, 30 mm) there is no significant difference compared with conventional IPMs. Presumably the fact that conventional catheters usually remain just a few days in situ could partly explain that uncommon phenomenon. Long-term implants as telemetric intraparenchymal catheters may induce (chronic) damage to the surrounding tissue resulting from pulsations of the brain: the device is fixed because of the implantation technique. Thus, the tip of the catheter is irritating the brain tissue with every heartbeat-associated brain movement. Additionally, the initial local tissue trauma during P-tel insertion may disrupt the blood–brain-barrier [10, 18], and this could contribute to (vasogenic) oedema development. That theory, however, would be supported by the phenomenon of vanishing oedematous reactions after a certain time (in 48 patients; mean time for complete resolution, 80.7 days± 46.6). Equally conceivable is a mediator-induced inflammatory tissue reaction resulting from the implantation trauma. Fassbender et al. [11] inserted microdialysis probes into the brain of rats and could observe a significant release of interleukin-1ß—the key mediator of acute inflammatory response—within the first 24 h.

Interestingly, all P-tel catheters communicating with CSF (due to very dilated ventricles in 12 patients or catheter location in the relatively large endoscopic approach in ten patients) produced no oedematous alterations. Two mechanisms may be responsible therefore. CSF may act like a “lubricant”, reducing significantly irritating forces. On the other hand, circulating CSF could “wash out” oedematous formations or responsible substances as inflammatory mediators. Both theories would support the fact that brain oedema is usually not seen in the surrounding area of an EVD or ventricular shunt catheter.

Interestingly, localised abnormal MRI findings after deep brain stimulation (DBS) lead implantation have been already described in the literature [10, 33, 38]. Related incidences of perifocal oedematous reactions ranged from 6.3 to 39.0 %. Comparable to the presented study, almost all findings were not associated with clinical or infectious complications. Additionally, a complete vanishing of the cerebral oedematous reactions over time was also seen in the DBS studies. Consecutively, the authors mostly assumed the initial trauma during lead implantation being responsible for abnormal findings [10, 18, 33]. Another possibility that has to be taken into account refers to the material characteristics, especially their potential neurotoxicity. A large study dealing with polyurethane DBS leads could not prove related adverse effects to neuronal structures [21], whereas a major manufacturer in the U.S. recently attributed potential neurotoxic properties to polyurethane components [10]. However, the catheter of the P-tel device consists of the same material as the Raumedic Neurovent-P probe. The Neurovent-P is the company’s conventional intraparenchymal ICP monitor (without telemetric data transmission) that was introduced to the European market in 1997. According to in-house information, more than 50.000 catheters have been implanted so far. Until today, there have been no complaints or critical reports about abnormal findings in imaging studies.

Another interesting phenomenon refers to the observed contrast enhancements in the presented study. Contrast agent was applied in 77 patients; related enhancements could be detected in 22 cases. Regarding to the suspicious ring enhancing lesions (n=4), an actual brain abscess was only verified in one case. Slight punctate enhancements (n =18) can be considered as an accompanying phenomenon of catheter insertions. Chronic irritation of the surrounding parenchymal tissue due to regular brain pulsations may induce scarring and may be responsible for contrast enhancement. This would be consistent with the study of Kroin et al. [25] published in 2000. Post-mortem histological examinations of three brains revealed a slight loss of myelin and an accumulation of glial cells in the white matter adjacent to the catheter channel.

Clinical consequences

Clinical complications as well as their incidences are approximately comparable with the results presented in the common literature. It is worth noting that the completely different study designs and methods do not allow statements with statistical significance.

Oedematous reactions have not been observed (or described) in conjunction with conventional IPMs or EVDs so far. Presumably the significant difference in implantation time or the clinical circumstances indicating the insertion of an IPM or EVD (e.g. traumatic brain injury, brain bleeding, etc.) can explain the non-observance of that abnormal phenomenon. On the other hand, recently published data about cerebral oedema surrounding DBS leads might suggest a kind of “regularity” of intracranial long-term implants.

However, more specific analyses of these oedematous alterations (e.g. by stereotactic puncture) are necessary for final conclusions, both in P-tel probes and DBS leads. The actual and potential negative value of the observed oedematous reactions cannot be finally estimated. Local brain oedema in the frontal lobe might have an effect on the premotor area. Related damages would be hardly detectable by routine clinical examinations. Although MRI follow-up examinations could demonstrate a clear tendency of complete oedema resolution over time, late effects on the brain function are not predictable. In 2003, Fujioka et al. [14] could prove transient MRI changes after brief focal ischaemia being associated with late-onset mental impairments. But it has to be mentioned that these local MRI changes appeared as hypointensities in T2-weighted images, indicating non-oedematous reactions.

So far, most complications in the present study were associated with additional pathological findings (e.g. bacterial growth, other surgical procedures, intracerebral haematoma). A correlation between clinical impairment and local oedematous reactions could not be found.

However, the fact that all P-tel catheters with contact to the ventricular system (n=22) showed no oedematous reactions (and no clinical complications) is a serious basic approach to solve the problem. A longer telemetric catheter for intraventricular placement or puncture of the lateral ventricle with a Cushing cannula before inserting the P-tel probe can presumably reduce incidence of pathological findings in cranial imaging.

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Comment

This article presents an extensive and interesting account of the use and complications of telemetric implanted intracranial pressure (ICP) monitors during long-term use. As the indication for long-term (thus telemetric) ICP monitoring is obvious in selected cases the risks that this procedure carries should be evaluated. The present knowledge should be complemented by prospectively collected data on the use of telemetric ICP monitoring. In particular, the reported high incidence of oedema near the catheter tips might be further elucidated by prospective imaging.

Peter Siesjo
Lund, Sweden