Acta Neurochirurgica (2019) 161:1605–1617
https://doi.org/10.1007/s00701-019-03959-5

ORIGINAL ARTICLE - CSF CIRCULATION

Home telemonitoring of intracranial pressure

Christoph A. Tschan[1] · Victor F. Velazquez Sanchez[1] · Michael Heckelmann[1] · Sebastian Antes[2]

Received: 27 January 2019 / Revised: 30 March 2019 / Accepted: 24 May 2019 / Published online: 5 June 2019

Abstract

Background As technical progress advances, telemonitoring has become an important part of patient care in many areas of medical treatment. However, distanced surveillance of intracranial pressure (ICP) could not be established so far. With the recent introduction of a telemetric ICP measurement probe, new possibilities arise. Here, we report on a new home setup enabling home telemonitoring of intracranial pressure.

Methods Twenty patients suffering from disturbances of cerebrospinal fluid circulation, who underwent insertion of a telemetric ICP measurement probe, were provided with medical equipment to read ICP at home and save the data on an internet-enabled computer. Training in handling the equipment was performed during in-patient stay; recorded and uploaded ICP data was then analyzed online. Therefore, the treating medical team was able to access the ICP data via a secure internet connection while telephone conferencing with the patient.

Results Almost 7400 h of ICP data were recorded at home and evaluated via an internet connection according to the telemonitoring setup. This corresponds to an average record time of about 370 h per patient. ICP profiles were observed following endoscopic treatment, shunting procedures, or valve adjustments. The mean distance between the patients' residence and the consulting hospital was 172 km (range, 16–649 km).

Conclusions ICP measurements have become accessible for telemonitoring purposes. This new management of hydrocephalus reflects an alternative method in patient care, especially for those who live far away from specialized centers.

Keywords Intracranial pressure · Hydrocephalus · Home monitoring · Telemonitoring · Telemetric ICP measurement · P-tel

Introduction

The term "telemetric ICP monitoring" is widely used for applying a transdermal transducer to perform measurements of the intracranial pressure (ICP) [2–6, 12, 14, 16–18, 23]. In opposite to conventional percutaneous ICP probes, there is no direct wired connection between the intracranial pressure probe and the reader and monitor. The Neurovent P-tel probe (Raumedic, AG, Helmbrecht, Germany) is a fully implantable parenchymal passive pressure probe working based on electromagnetic inductivity. This enables transdermal power supply and ICP data transfer.

The value of ICP monitoring in patients with hydrocephalus and other neurological diseases caused by disturbances of the cerebrospinal fluid (CSF) circulation with complex clinical presentation is well described [4, 9–11, 13, 21, 22]. The development from repeated overnight or short-term ICP monitoring with external ventricular drains (EVD) or percutaneous parenchymal ICP probes to long-term ICP monitoring techniques with fully implantable telemetric devices constitutes an important step in the diagnostic work-up and treatment of hydrocephalus since it allows to measure in the patient everyday environment and for a significantly longer period of time [1, 4–6, 17].

A telemetric and fully implantable probe enables ICP monitoring in an out-patient setting which reflects advantages compared to hospitalization or even bed bound scenarios. So far, home monitoring with telemetric probes has been limited to a setting in which the measurements were performed by the

This article is part of the Topical Collection on *CSF Circulation*

The content of the paper has not been presented in oral or poster form at a conference.

✉ Christoph A. Tschan
tschan@ludmillenstift.de

[1] Department of Neurosurgery, Hospital Ludmillenstift, Ludmillenstr. 4-6, 49716 Meppen, Germany

[2] Department of Neurosurgery, Saarland University Medical Center and Saarland University Faculty of Medicine, Homburg, Saar, Germany

patients at home and could be viewed and evaluated by the treating neurosurgeon only on out-patient visits [1, 6, 23]. The data storage volume of the monitor (MPR 1 Datalogger, Raumedic AG, Helmbrechts, Germany) restricts the amount of measurements to a total time of about 72 h in 5 Hz recording or 15 days in 1 Hz recording. This might prompt frequent visits at the out-patient clinic.

Home telemonitoring describes a setting of remote surveillance of patients, who are living in their everyday environment, with the possibility for the treating physician to access the data or receive online alarms. Home telemonitoring is used in a more restrictive sense and encompasses the use of audio, video, and other telecommunication technologies to monitor the patient's status at a distance [15, 19]. It requires a special technical setup enabling to save performance of measurements and secure digital data storage at home [7]. This is mostly established by a computer device located in the patient's home, which can be exclusively accessed via the internet by the treating medical team. Another possibility is the automatic forwarding of the gathered information to the remote computer system of the treating medical center [7, 15].

Home telemonitoring has been established for chronic diseases in many medical fields for health issues as for example pulmonary conditions, diabetes, hypertension, or cardiovascular diseases [7, 8, 15, 19, 20]. In these areas, home telemonitoring has shown many advantages compared to conventional managing. It has shown that patients were able to handle the advanced technical devices quite well on their own at home. Moreover, accurate and reliable data could be produced in almost all cases [19].

Monitoring of ICP in neurosurgical patients suffering from chronic diseases such as hydrocephalus or benign intracranial hypertension (BIH) has been proven to be a sufficient and helpful tool. This is especially true in cases of recent CSF diversion by ventriculostomy or shunting [4, 5, 12, 14, 23]. The main advantages refer to the fact that objective measurements help to evaluate the clinical condition of the patients while the subjective symptoms often remain unspecific. This might for example even facilitate to distinguish between under- and overdrainage in shunt-treated patients, which can be a difficult task otherwise [4, 5].

Furthermore, "illustrated" or "displayed" physiological intracranial conditions might help to ease the patient's concerns [4, 5]. For the clinician, long-term ICP monitoring delivers valuable information. Especially overnight monitoring and measurements during everyday activities and circumstances that might cause symptoms are valuable in problematic and challenging cases of a disturbed CSF circulation [4, 13, 21].

Direct access to the ongoing ICP measurement might be desired both in acute situations and during regular follow-up examinations. In conventional home monitoring, out-patient appointments are necessary to evaluate the recorded ICP. However, acute visits should be achievable if a disturbing situation requiring immediate analysis of the ICP profile occurs. Depending on the infrastructure and distance of the patient to the medical center, visits can be time-consuming and effortful for the patient. In order to enable a more practicable remote access to the patient's ICP, the authors established a setup in which online access to the recorded data is feasible.

Methods and materials

Between August 2014 and November 2018, the authors applied the home telemonitoring technique in 20 patients. Medical decisions regarding further treatments were based on gathered home ICP data and clinical symptoms.

The telemetric ICP measurement system

The ICP monitoring system "Neurovent P-tel" has been described extensively before [1–4, 6, 14, 16–18, 23]. In short, it consists of a fully implantable probe with a piezoresistive pressure transducer. It omits an own power source and needs to be activated transdermally by an external solenoid coil, the reader unit (TDT1 readP, Raumedic AG, Helmbrechts, Germany). Electromagnetic inductivity enables power supply from the reader to the probe and simultaneous data transmission from the probe to the reader, which is connected to the monitor and storage unit (Datalogger MPR-1, Raumedic AG, Helmbrechts, Germany). Figure 1 depicts the telemetric measuring system.

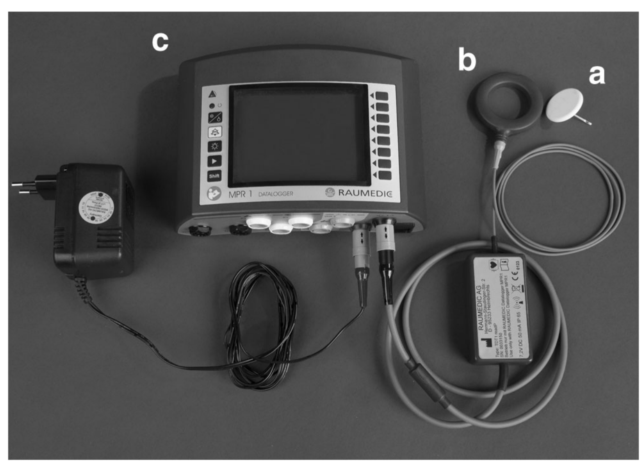

Fig. 1 Photograph of the telemetric ICP measurement system. The P-tel probe (A) is a fully implantable passive device with a piezoresistive pressure transducer at the catheter tip. It is activated via an electromagnetic field generated by the reader unit (B). Electromagnetic inductivity enables power supply from the reader to the probe and simultaneous data transmission from the probe to the reader. The reader is connected to the Datalogger MPR-1 (C), which displays and stores the ICP data

Surgical insertion and removal of the probe

The implantation of the P-tel probe is usually performed under general anesthesia. The surgical technique has been described in detail before [4, 23]. Through a pre-coronal burr hole, the catheter of the probe (30 mm in length and 1.67 mm in diameter) is placed into the frontal brain parenchyma, while the ceramic housing remains on the skull surface. In general, the probe is inserted on the left hemisphere, unless a left-sided shunt gives reason to choose the right side. Directly after insertion, a first measurement is obtained in the operating theater to assure the functioning of the probe.

When ICP monitoring is accomplished, the P-tel probe has to be explanted surgically. With regard to regulatory affairs, this should be carried out not later than 3 months after insertion. At the patient's request, insertion periods can be extended. The explantation consists simply of the reopening of the former skin incision and mobilization of the subcutaneously located ceramic housing. The whole procedure can be performed in local anesthesia [2, 4].

Patients

Home telemonitoring of ICP was applied in 20 selected patients suffering from disturbances of cerebrospinal fluid (CSF) circulation. Indications for P-tel insertion can be assigned to one of the following categories:

Group A primary diagnostic work-up and surveillance after CSF diversion
Group B verification and therapy support in shunt dysfunction
Group C surveillance after endoscopic third ventriculostomy (ETV)

General patient data including main diagnosis, past surgical history, and indication for P-tel insertion are summarized in Table 1. All patients were treated at the Department of Neurosurgery at the Hospital Ludmillenstift in Meppen, Germany. The age ranged from 9 to 65 years with an average of 33.2 ± 16.3 years. Four patients were younger than 18 years at the time of P-tel insertion. The gender ratio was 15 females to 5 males.

Home telemonitoring

In order to expand ICP monitoring to home telemonitoring, which allows the clinician remote access to the ongoing or recorded measurements, the patients were equipped with an internet-enabled laptop. The laptops contained the Datalog software (Raumedic AG, Helmbrechts, Germany) to connect the MPR-1 (to store ICP data) and the TeamViewer software (version 13, TeamViewer GmbH, Göppingen, Germany) to establish a secured one-to-one remote access.

During the initial hospital stay for insertion of the P-tel probe, all patients were intensively trained in handling the system to perform ICP measurements at home. This also includes the connection of the MPR-1 to a computer, the basic usage of the Datalog software, and the launch of TeamViewer to establish a remote connection with the hospital. Once the patient was successfully instructed, discharge and the first virtual conference for remote ICP analysis was scheduled. After discharge from the hospital, all patients continued telemetric ICP measurements at home. Patients were encouraged to measure during different daytime activities (e.g., walking and working) and nighttime sleep.

To share the measurements with the treating medical team, the patients connected the computer to the internet at the appointed date. Via simultaneous telephone contact, the clinician was provided with the individual password to log on securely on the TeamViewer remote access of the patient's computer. Regarding connection and data security issues, the TeamViewer software uses a 256-bit advanced encryption standard (AES) algorithm. Furthermore, two-factor authentication (username, password, and individual session code sent on a mobile device) may protect from unauthorized access as well. It should be noted that patients do not send individual data (e.g., ICP values) unsecured via the internet. Instead, their data is only viewed and analyzed per remote access.

Remote analysis of homely recorded ICP data

After establishment of the telephone connection and remote access with the computer, the patient's condition and symptoms were discussed and noted. This included frequency and quality of headaches as well as day and night or position-related symptoms. Depending on the individual questioning, mean ICP values for different body positions (mainly standing and lying down), peak maximum and minimum values, the amount of low- and high-amplitude B-wave activity, and the pulse pressure amplitude were obtained and evaluated. Referring to this, the possibilities of analyzing telemetrically gathered ICP data in a standardized approach have been described before [4, 18]. At the end of the virtual conference, further treatment options and possible out-patient or in-patient consultations were planned with the patient (Fig. 2).

Results

ICP recordings

Intracranial pressure was recorded either during hospitalization or at home. The first measurements took place in hospital following the insertion of the probe. The initial hospital stays

Table 1 General patient data

Pat ID	Sex	Age (year)	Etiology of CSF disturbance	Past surgical history	P-tel indication
1	f	31	BIH	n/a	A
2	f	23	BIH	n/a	A
3	f	36	BIH	n/a	A
4	f	53	Aqueduct stenosis	ETV, septum pellucidotomy, foraminoplasty	A
5	f	17	Aqueduct stenosis	ETV, Re-ETV, VP shunt, multiple revisions, shunt removal	A
6	f	23	Dandy Walker variant	n/a	A
7	f	52	Dandy Walker variant	n/a	A
8	f	52	BIH	VP shunt	B
9	f	34	Posthemorrhagic hydrocephalus	VP shunt	B
10	m	48	Postinfectious hydrocephalus	VP shunt	B
11	f	20	MMC/Chiari	VA shunt, multiple revisions	B
12	f	26	Aqueduct stenosis	ETV, VP shunt	B
13	f	15	Dandy Walker syndrome	VP shunt, multiple revisions	B
14	f	45	BIH	LP shunt, LP shunt ligation, VP shunt	B
15	m	24	Complex cerebral malformation	VA shunt	B
16	m	52	Posttraumatic hydrocephalus	VP shunt, multiple revisions	B
17	m	65	Aqueduct stenosis	n/a	C
18	f	11	Blake's pouch cyst	n/a	C
19	m	27	Aqueduct stenosis, infratentorial cyst	Aqueductoplasty, cyst fenestration, VA shunt, shunt removal	C
20	f	9	Aqueduct stenosis	VP shunt	C

A, group A: primary diagnostic work-up and surveillance after CSF diversion; *B*, group B: verification and therapy support in shunt dysfunction; *BIH*, benign intracranial hypertension; *C*, group C: surveillance after endoscopic third ventriculostomy; *CSF*, cerebrospinal fluid; *f*, female; *LP*, lumboperitoneal; *n/a*, not available; *m*, male; *MMC*, meningomyelocele; *VA*, ventriculoatrial; *VP*, ventriculoperitoneal

also included the onset of the diagnostic work-up and the training of the patients in handling the P-tel system. Further hospitalization(s) became necessary for possible therapeutic interventions (e.g., shunt implantation) and final P-tel removal (Fig. 2). The total amount of in-patient treatment days counted to 519. This corresponds to an average hospitalization time of 26.0 ± 16.8 days (range, 6–65 days) per patient. During these occasions, a subsumed ICP recording time of 3243 h could be collected (162.2 ± 162.9 h per patient). The proportionately biggest amount of measurements was performed at home. The overall home monitoring time was 7394 h (308 days). This is a proportion of almost 70% of the entire ICP recording amount (10,637 h) and corresponds to averagely 369.7 ± 366.6 h per patient. Table 2 shows the total and mean measuring times of the whole cohort.

During the 4-year observation period, a total of 155 virtual conferences for remote ICP analysis were held. This corresponds to an average of 7.8 remote analyses per patient (range, 0–25). Remote analyses were carried out over an average distance of 171.8 ± 167.0 km. Distances from the patients' residences and the medical center ranged from 16 to 649 km. A session of remote ICP analysis took about 30 min but varied from patient to patient. Exact lengths of telephone calls were not documented. Table 3 depicts the key figures of home telemonitoring and remote analyses.

Therapeutic consequences of ICP recordings

The P-tel probe was inserted for an average of 278.5 ± 250.1 days per patient (range, 42–861 days). Therapeutic consequences described below are related strictly to this implantation period. Moreover, it is worth noting that all medical decisions were derived from the homely recorded and remotely analyzed ICP profiles.

Following P-tel insertion, 17 patients underwent further therapeutic interventions because of pathologic ICP recordings. Thirteen patients had one or more surgical procedures, while the other 4 could be treated only with shunt valve adjustments. The remaining 3 cases without indication for further treatment showed a regular postoperative course after ETV (Pat. ID 17 and 18) or a normal ICP profile during the primary diagnostic work-up (Pat. ID 7). In summary, the telemetric ICP measurements resulted in 21 different surgeries and 76 shunt valve adjustments.

In group A ($n = 7$), initial diagnostic ICP measurements resulted in VP shunt insertions in 5 patients, endoscopic third ventriculostomy (ETV) in one patient, and no further treatment in another patient (normal ICP). Six patients were able to join the virtual conferences ($n = 41$, in average 6.8 per patient). Home telemonitoring of ICP could confirm a regular postoperative course of the ETV-patient. In contrast, all shunt-

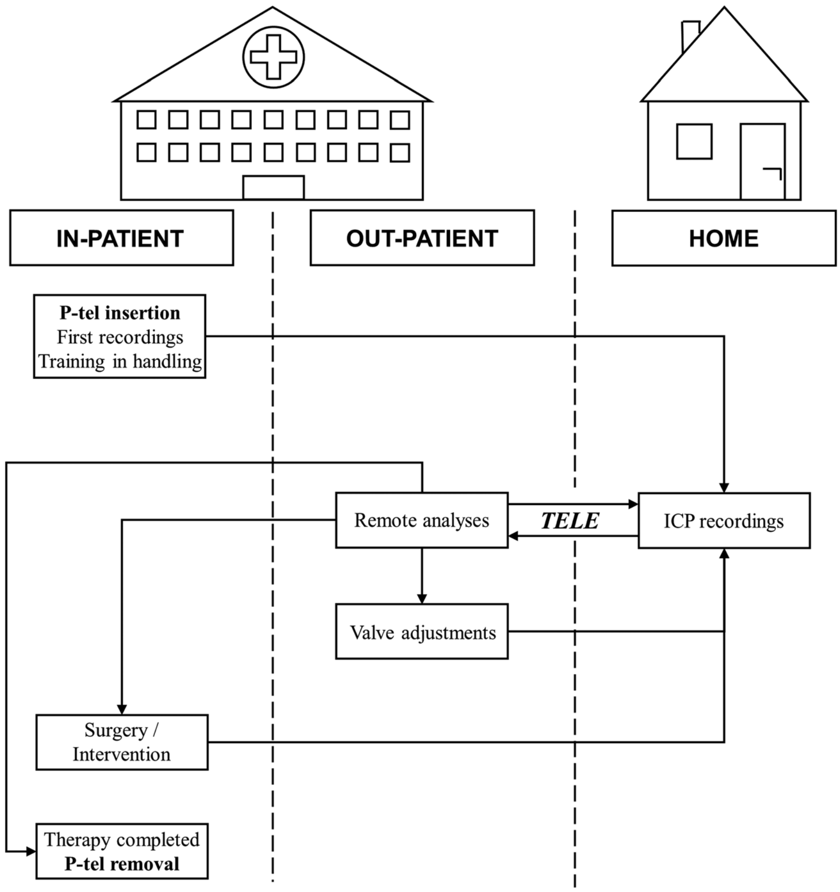

Fig. 2 Scheme of the home telemonitoring setup. The diagnostic work-up always starts with the first in-patient treatment for P-tel insertion. After discharge from hospital, patients measure at home. During the virtual conferences (*Tele*), the medical team analyzes the homely recorded ICP data via remote access. These remote analyses may result either in shunt valve adjustments at out-patient visits, surgical interventions in the hospital, or completion of the therapy with removal of the telemetric probe. In case of valve adjustment or surgery, another virtual conference for remote analysis is scheduled. This loop (remote analysis → valve adjustment / surgery → ICP recording → remote analysis) is repeated until completion of the therapy

treated patients required several valve adjustments ($n = 29$) and out-patient services ($n = 25$).

In group B ($n = 9$), suspected shunt dysfunction could be confirmed in all cases. Seven patients suffered from overdrainage and two from underdrainage. Almost half of the patients were successfully treated with ICP-guided valve adjustments, the other five patients underwent one or more surgical interventions (e.g., shunt augmentation with a gravitational valve) to get rid of the shunt-related problems. In this subgroup, a total of 91 remote analyses (in average 10.1 per patient) were carried out resulting in 41 out-patient appointments (in average 4.6 per patient) for shunt valve adjustments.

In group C ($n = 4$), home telemonitoring of ICP was intensively used to supervise the postoperative course after ETV. Twenty-two remote analyses (in average 5.5 per patient) were necessary to confirm a regular long-term ICP profile in three cases and a pathologic ICP profile in one case. One of the patients with an ETV-success underwent additional shunt removal surgery. The patient with the pathologic ICP profile received a VP shunt and two further valve adjustments.

Table 4 summarizes all therapeutic efforts including in-patient and out-patient treatments.

Table 2 ICP recording times

	Total ICP data	Hospital ICP data	Home ICP data
Measuring time in h			
Sum	10,637	3243	7394
Mean	531.9 ± 408.7	162.2 ± 162.9	369.7 ± 366.6
Range	95–1754	17–690	26–1536

ICP intracranial pressure

Complications and limitations

In this series, no relevant clinical complications associated with the insertion of the telemetric ICP measurement probe appeared. This especially included seizures, wound healing disorders, or intracranial infectious incidences. During the whole observation period, no emergency necessitating an immediate in-patient treatment (e.g., due to critical ICP) occurred. None of the patients presented themselves at another hospital due to health problems or inconsistencies with the primary treating team. Within the chosen group of patients, 18 out of 20 had no handling difficulties with the home telemonitoring setup. The patients were able to perform the measurements independently and could save the recorded ICP data with the Datalog software on their computers. No issues were encountered establishing the TeamViewer remote access to the ICP readings. Two patients could not overcome

Table 3 Home telemonitoring of ICP

Pat. ID	Remote analyses (*n*)	Recorded ICP data at home (h)	Share in total measuring time (%)	Distance to hospital (km)
1	3	688	89.6	42
2	5	200	43.0	100
3	9	537	87.5	176
4	8	677	87.0	52
5	13	699	63.0	416
6	0	26	10.0	37
7	4	55	33.1	42
8	14	390	85.9	63
9	0	193	51.1	386
10	5	171	77.4	104
11	18	1536	87.6	229
12	25	480	60.5	159
13	5	100	68.5	42
14	7	73	76.8	157
15	8	118	14.6	365
16	9	177	55.8	140
17	2	164	67.8	649
18	12	756	92.5	235
19	5	125	61.0	16
20	3	229	93.1	25
Sum	155	7394	n/a	n/a
Mean	7.8 ± 6.2	369.7 ± 366.6	65.3 ± 24.9	171.8 ± 167.0

ICP intracranial pressure, *n/a* not available

difficulties in establishing a sufficient internet connection. In these patients, the measurements were analyzed during the out-patient visits, as in the conventional home monitoring setup.

Exemplary illustrative clinical cases

Case 1 (Pat. ID 1)

A 31-year-old woman was suspected to suffer from benign intracranial hypertension. Clinically, she presented constant holocephalic oppressive headaches and the ophthalmological inspection showed papilledema. The MRI presented classical slit like ventricles. A P-tel probe for further objectification was inserted. In the first measurement, a high rate of pathologic B-waves in conjunction with an increased pulse pressure amplitude was noticed (Fig. 3a, b). Both, the B-wave frequency and pulse pressure amplitude improved after lumbar puncture (Fig. 3c). Among these measurements, a VP shunt with an adjustable differential pressure and adjustable gravitational valve (proSA-Shuntsystem, Christoph Miethke, Potsdam, Germany) was implanted. The patient was then sent home with the equipment to perform home telemonitoring of ICP. During the first virtual conferences, she reported headaches and dizziness. Remote ICP analyses showed overdrainage leading to the decision to adjust the valves (Fig. 3d). Finally, her symptoms resolved. In this case, the P-tel probe supported the initial diagnosis of benign intracranial hypertension and home telemonitoring was crucial to obtain the perfect adjustments of the shunt valves. The final measurements revealed a clear reduction of B-wave activity (< 20%), normalized pulse pressure amplitude (3–4 mmHg), and acceptable mean ICP values by day (− 4 mmHg) and night (+ 10 mmHg). This patient lived 42 km from the hospital and measured 688 h at home.

Case 2 (Pat. ID 11)

This case is about a 20-year-old female with congenital hydrocephalus in relation with myelomeningocele, tethered cord, and Chiari malformation. She was already shunt-treated (VA shunt) and presented a long medical history with multiple revision surgeries in the past. At the time, she presented herself at the out-patient clinic, she reported persistent headaches, and she showed symptoms of overdrainage. The existing shunt system consisted of an adjustable differential pressure (DP) valve and a gravitational (G) valve with a fixed pressure setting. We decided to implant a P-tel probe to control the proper function of the shunt system. Her mother was instructed and helped to install the home telemonitoring setup. The measurements at home showed persistent negative ICP values in the lying position, in mean below − 15 mmHg, intensified when she was in sitting position (Fig. 4a). At the first out-patient control, it could be noted that the DP-valve was not adjustable anymore. Thus, we revised the shunt and implanted a new proSA-Shuntsystem. The first measurements after the revision still showed too low ICP values but an improvement could be recognized (Fig. 4b). At another out-patient visit, the G-valve was adjusted to a higher opening pressure and further home recordings of ICP followed (Fig. 4c). She lived 229 km from the hospital and measured 1536 h at home. The stepwise improvement of the ICP profile could be observed during 18 different virtual conferences. Most recently, the ICP profile proved to overcome overdrainage and her long-term headaches completely vanished (Fig. 4d). In the sitting position, ICP did not fall below − 5 mmHg anymore. So far, she has visited the out-patient clinic 2 times only.

Case 3 (Pat. ID 7)

A 52-year-old woman was referred from another hospital and initially admitted to the psychiatric clinic due to sudden onset of cognitive disorder with a progressive gait disturbance and psychosis. At first, the psychosis was treated medically, and the mental state of the patient stabilized. The CCT and MRI showed a Dandy Walker variant, with signs of an occlusive

Table 4 Therapeutic consequences of telemetric ICP measurements

Pat. ID	Initial diagnostic ICP measurement	Surgical consequences	Valve adj. (*n*)	Out-patient visits (*n*)	Hospitalization (day)
1	Elevated ICP	VP shunt	2	8	48
2	Elevated ICP	VP shunt	2	3	31
3	Elevated ICP	VP shunt	10	4	26
4	Elevated ICP	VP shunt	7	7	25
5	Elevated ICP	a) VP shunt b) Shunt assistant c) Adj. gravitational valve	8	3	37
6	Elevated ICP	ETV	n/a	2	22
7	Normal ICP	n/a	n/a	1	27
8	Overdrainage	n/a	12	13	6
9	Overdrainage	n/a	3	2	10
10	Overdrainage	n/a	2	1	28
11	Overdrainage	Shunt revision	3	2	19
12	Overdrainage	Shunt revision	8	12	24
13	Overdrainage	Adj. gravitational valve	3	2	6
14	Overdrainage	a) Adj. gravitational valve b) LP shunt removal c) Spinal duraplasty	6	3	62
15	Underdrainage	a) Shunt revision b) Shunt removal c) VP shunt (new)	4	3	65
16	Underdrainage	n/a	4	3	25
17	n/a	n/a	n/a	2	22
18	n/a	n/a	n/a	3	7
19	n/a	VP shunt	2	5	22
20	n/a	Shunt removal	n/a	1	7
Sum	n/a	n/a	76	80	519
Mean	n/a	n/a	5.1 ± 3.2	4.0 ± 3.4	26.0 ± 16.8

adj. adjustable/adjustment, *ETV* endoscopic third ventriculostomy, *ICP* intracranial pressure, *LP* lumboperitoneal, *n/a* not available, *VP* ventriculoperitoneal

hydrocephalus. We decided to perform an ICP measurement to figure out whether symptoms can be related to the findings of the imaging. Therefore, a P-tel probe was implanted, and the patient instructed to perform home telemonitoring. The first measurements at the clinic proved physiological values. There was no evidence of an increased pathologic slow wave activity (A- or B-waves) at night (Fig. 5a) or an elevated pulse pressure amplitude (Fig. 5b). The ICP profile showed a calm and smooth curve progression with pressure values around − 5 mmHg by day and + 5 mmHg by night (Fig. 5c). The measurements at home confirmed these physiological findings. Even a further decrease of the pressure could be observed (Fig. 5d). The mean ICP circled between − 7 mmHg (by day) and + 1 mmHg (by night). Thus, no further treatment was needed. This patient measured at home for 55 h, mostly in symptomatic periods. In this case, telemetric ICP monitoring and especially the measurements at home helped to rule out symptomatic hydrocephalus and enabled an objective decision against surgical treatment such as ETV or shunting. Furthermore, home telemonitoring could reduce out-patient visits of this patient ($n = 1$), who lived 42 km away from the hospital.

Discussion

For a better understanding, it is necessary to define the terminology used. Generally, there are 3 different measuring methods:

- Short-term monitoring
- Home monitoring
- Home telemonitoring

Short-term monitoring—as part of the primary diagnostic work-up—lasts about 2–3 days and can be performed with a conventional (e.g., intraparenchymal monitor) or telemetric probe [4, 9]. Home monitoring of ICP means that patients are supplied with special equipment to perform recordings at home. Minimum requirement is a special local storage unit

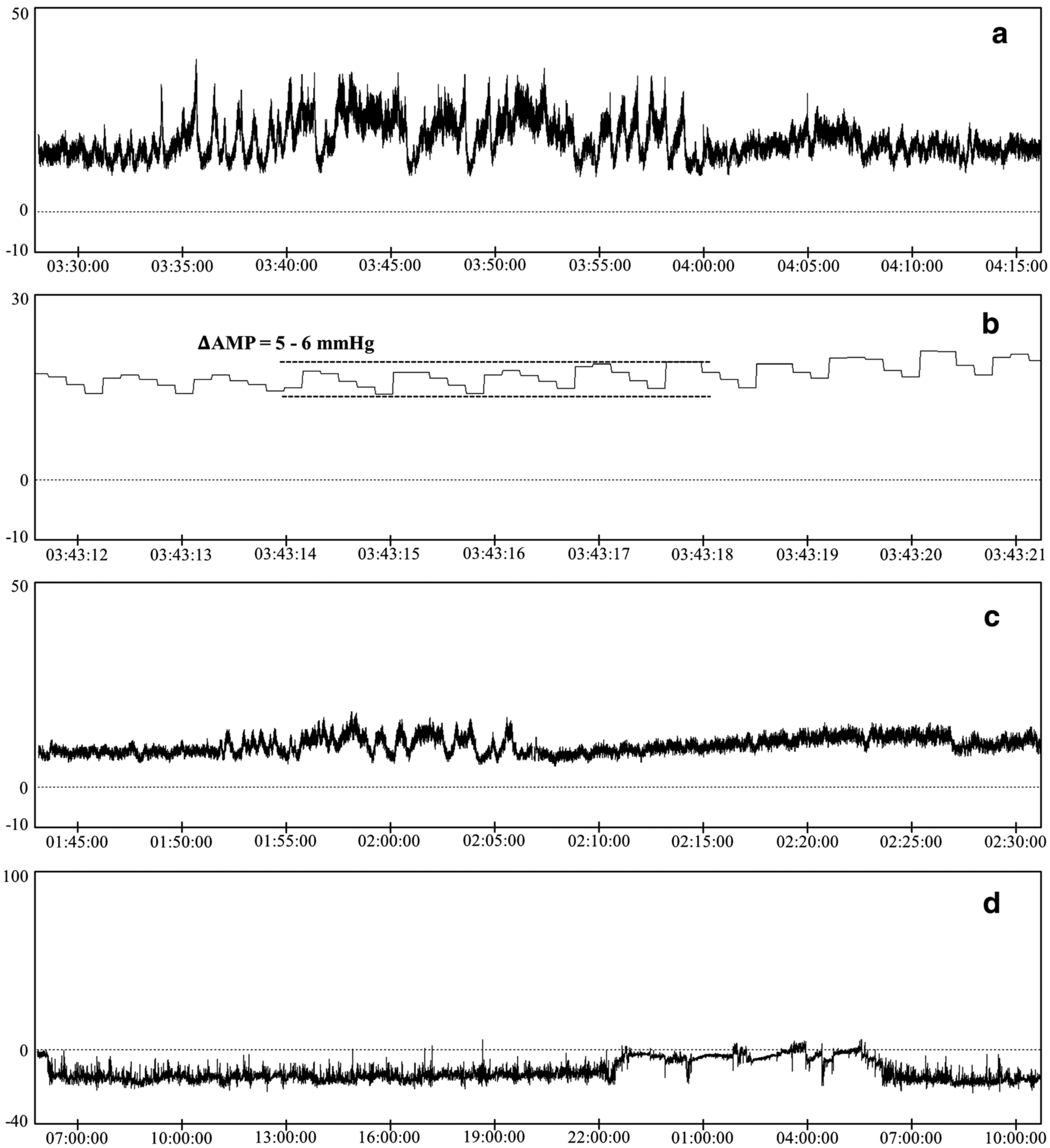

Fig. 3 Representative pre- and postoperative ICP recording parts in BIH (case 1). The diagnostic ICP measurement at night showed a slightly elevated mean ICP of + 15 mmHg in conjunction with low- and high-amplitude Lundberg B-waves (**a**). The pulse pressure amplitude during night, estimated at 5–6 mmHg, indicated restricted compliance (**b**). After lumbar puncture and withdrawal of a few milliliters of CSF, a clear improvement of the ICP profile could be recognized (**c**). The mean ICP decreased below the level of + 10 mmHg at night and only a few low-amplitude B-waves occurred. This positive response led to the decision to insert a ventriculoperitoneal shunt system. A few weeks later, the patient reported progressive headaches and dizziness, especially in the upright position. Home monitoring revealed very low ICP of − 15 to − 20 mmHg during daytime and negative ICP around −5 mmHg at night (**d**). Two further valve adjustments to overcome overdrainage followed. Recently, the patient's symptoms resolved and the P-tel probe could be removed

implying that duration of the recordings is dependent on the capacity of the system. Another option is home telemonitoring of ICP. The difference to conventional home monitoring is reflected by the "unlimited" storage capacity. In fact, patients periodically transfer their ICP data on a computer to free up storage capacity on the special local storage unit. This also implies that patients no longer need to attend the hospital when the capacity of the local storage unit is exhausted.

Home telemonitoring represents an advancement of ICP monitoring, which is adjusted to the needs of the patients using the currently available technology. Nowadays, it is possible to measure ICP values at home and to perform virtual conferences to make medical decisions, which are based on intracranial conditions occurring in normal daily life. The importance of this approach has already been proven in other medical fields like cardiology, pneumology, and diabetology

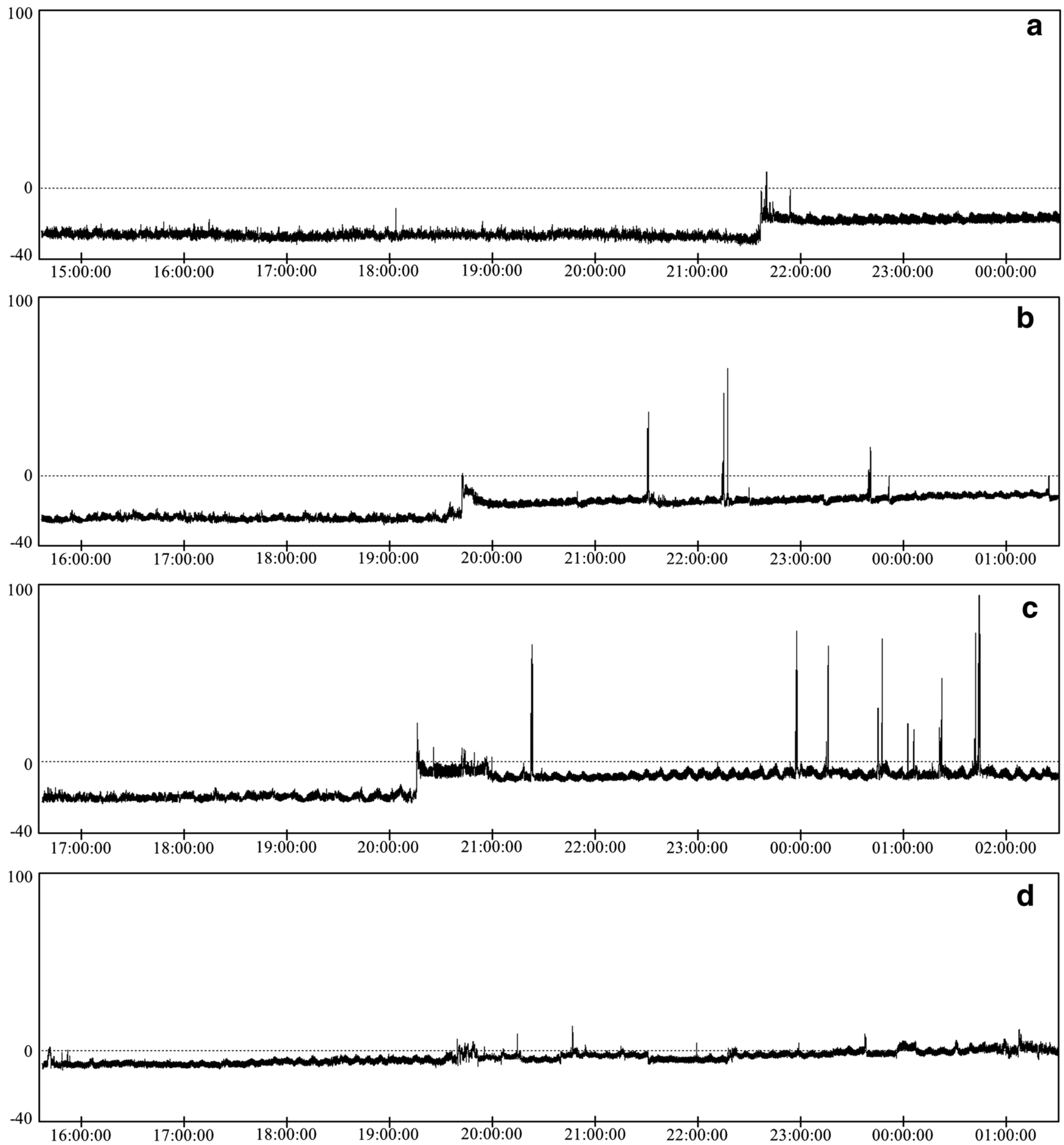

Fig. 4 Representative 10-h ICP recording parts in CSF overdrainage (case 2). The first diagnostic ICP measurement proved significant overdrainage being responsible for persistent headaches. ICP by day was as low as − 30 mmHg (**a**). After revision of the shunt system, a minimal improvement could be recognized. But home monitoring showed persistent overdrainage with negative ICP values in the lying position, in mean below − 10 mmHg, intensified in the sitting position (**b**). The gravitational valve was re-adjusted to a higher opening pressure resulting in an elevation of the ICP values (**c**). Finally, another adjustment with pressure level increases was associated with clinical well-being. Daytime ICP recently circled around − 5 mmHg and nighttime ICP was slightly positive between 0 and + 5 mmHg (**d**). Due to home telemonitoring technique, only two out-patient visits were necessary to successfully treat this patient. Main treatment and decisions were based on a total of 18 remote analyses

where home telemonitoring is an important and indispensable tool in the management of chronic diseases [7, 8, 15, 19, 20]. As shown by Paré et al. [19], home telemonitoring in these fields empowers patients, influences their attitudes and behaviors towards their disease, and improves medical conditions. With ICP home telemonitoring enabling accurate and reliable data production, there is no doubt that the abovementioned improvements can be extrapolated to it.

The handling of the hardware devices and software tools (Datalog and TeamViewer) is easy and feasible [4, 23]. Two patients were not able to overcome internet connection problems. Probably, a more precise evaluation of the patients' computer skills and mental smartness before inclusion in this study would have been helpful. However, this study proved that home telemonitoring of ICP is generally feasible. Twenty patients collected a huge and reliable amount of pressure data

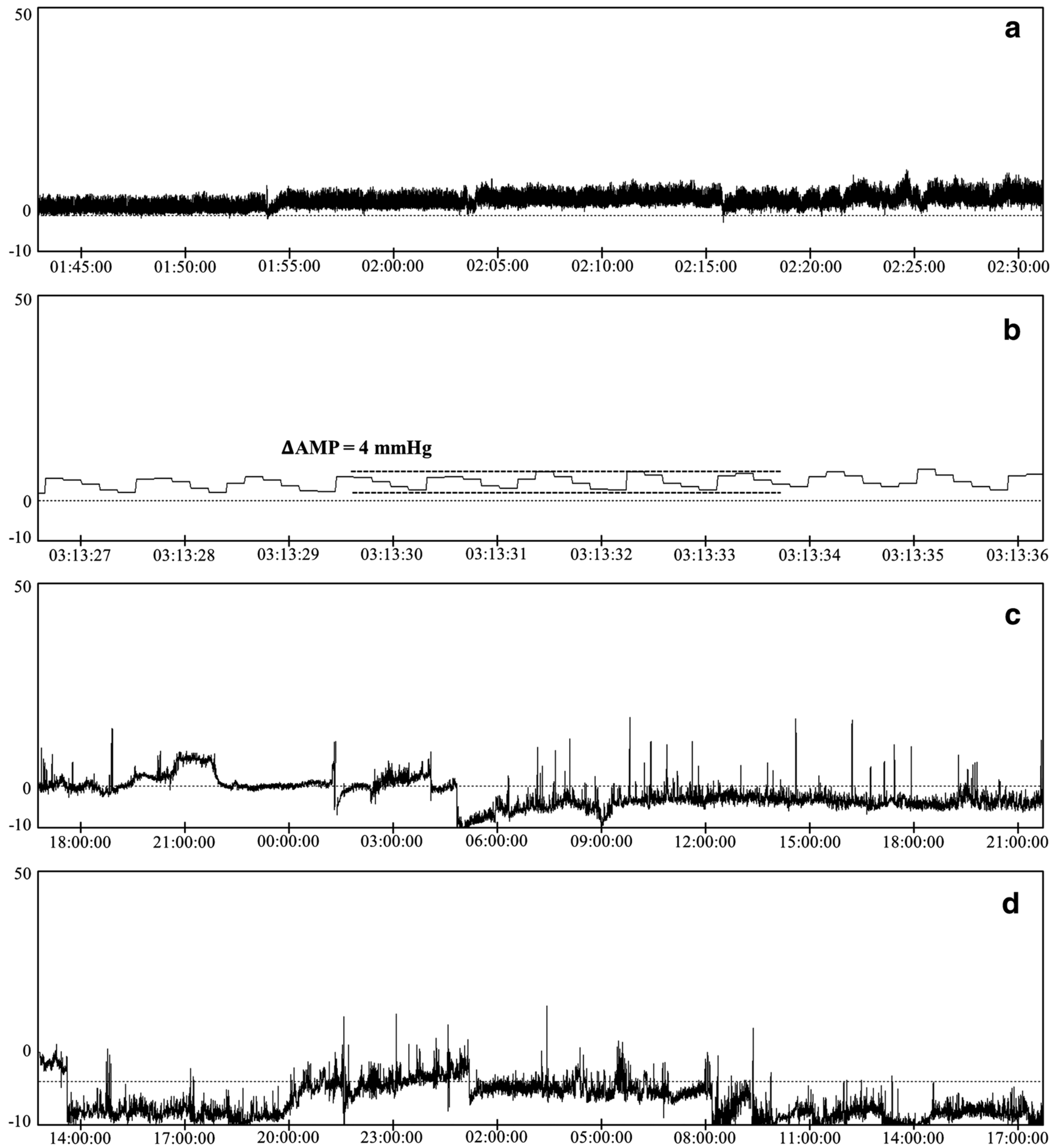

Fig. 5 Representative ICP monitoring parts of an inconspicuous measurement (case 3). The first three images (**a**, **b**, **c**) reflect recordings during the initial hospital stay. There was no significant pathologic slow wave activity or occurrence of suspicious ICP peaks (**a**). The pulse pressure amplitude, on average at 4 mmHg, indicated a non-restricted intracranial compliance (**b**). As well, the 24-h recording confirmed normal ICP values by day and night (**c**). A few weeks later, the patient started to measure at home. The 24-h measurement once again excluded symptomatic hydrocephalus (**d**). After a total of 55 h of home telemonitoring, an out-patient appointment was scheduled for returning the equipment and fixing another date for P-tel explantation

at home (7394 h). This amount was more than twice as high as the recorded ICP data during hospitalization (3243 h).

Decision-making in complex hydrocephalus is simplified for the physician [1, 23]. Due to home telemonitoring technique, the medical team can rely on valid and reliable patient data. The presented approach also allows a focus appointment at the out-patient clinic since medical decisions have already been made during the virtual conferences. A good example for this is the 52-year-old female with the overdraining shunt (Pat. ID 8). This patient visited the out-patient clinic 13 times to optimize the valve settings. These appointments were not as time-consuming as they would have been if she had to explain her symptoms from the beginning all over again.

In this study, scheduled remote analyses worked properly. As mentioned before, in the home telemonitoring setup, access to ICP measurements should also be possible in acute emergency situations. This is especially important for patients (and doctors) with a long commute to the hospital. An acute incident with dramatic clinical symptoms or even loss of consciousness did not occur in this series. In most cases of arising symptoms or clinical deteriorations, the patients called the hospital and appointed a spontaneous virtual conference for the next day or the day after. At present, it is not possible to assess whether real emergencies can be safely handled by home telemonitoring purposes or not. In any case, a special emergency plan ought to be developed (24/7-hotline, staff training, permanent access to the main computer for remote analyses, etc.).

Patients of this study did not present themselves at another hospital like it usually happens with hydrocephalus patients. Indirectly, this proves that home telemonitoring gives patients a sense of near and individual treatment, and better individual follow-up. The patients appreciate the monitoring since it underpins their subjective complaints with objective diagnostic results.

Home telemonitoring of ICP takes up more time for the patient and the physician compared to regular out-patient appointments. In this study, a total of 155 virtual conferences for remote ICP analyses were carried out. With analysis sessions of averagely 30 min, the medical team spent almost 80-h extra time in addition to their regular job. This is a 2-week full-time employment. Unfortunately, personal expenses are not covered in the German health care system so far. Home telemonitoring patients must be equipped with an MPR-1 Datalogger (local storage unit) and a laptop. Usually, the MPR-1 is an item on loan when using the P-tel system regularly (no extra costs). It should, however, be considered that the device is not available for other patients during the home telemonitoring process.

So far, there is no data to compare or explain on which basis patients should be selected and included for the home monitoring or home telemonitoring process. However, the primary diagnostic work-up to confirm elevated or pathologic ICP (e.g., suspected NPH or BIH) certainly does not require measurements at home. Therefore, it is stated that continuous short-term ICP recordings for 2–3 days are sufficient to make the diagnosis [4, 9–11, 22]. In group A, the first measurements could actually have taken place during the initial hospital stay. The question (surgery: yes or no?) in these patients would have been easy to answer in the conventional treatment regimen. Yet, patients who recently underwent shunt surgery qualify for home recordings [4, 5, 12, 14, 23]. It usually takes several weeks after shunting until new pressure ranges have been leveled. In such cases, long-term ICP recordings at home are sufficient to timely recognize emerging over- or underdrainage situations [2, 4, 5]. In this study, a total of 5 patients of group A were diagnosed to suffer from a disturbed ICP profile and underwent shunt surgery. Postoperatively, they all benefitted from the long-term recordings at home. Suboptimal valve settings and consecutive over- or underdrainage situations could be recognized early during the remote analyses (in average 7.6 per patient) resulting in a total of 29 valve adjustments (in average 5.8 per patient). This potentially avoided worse drainage-related problems in these patients (case no. 1).

It may be discussed if home telemonitoring was necessary in the patient with the coincidence of Dandy Walker variant and psychosis (case no. 3). Elevated ICP could be excluded during the initial hospital stay. Therefore, one single short-term ICP measurement for 2–3 days would have been sufficient. In this special case however, the home telemonitoring process provided other advantages. The medical team got another confirmation of normal ICP (Fig. 5d), and the patient felt taken seriously and carefully treated.

The therapy of manifest drainage-related problems is a difficult task, especially in overdrainage [4, 5, 14]. It is rarely the case that symptoms resolve after one or two valve adjustments. It has been demonstrated that ICP measurements can simplify this issue [4, 5, 21, 23], but the crucial points are time and slow/stepwise valve adjustments [4, 5]. In such cases, home monitoring or home telemonitoring meet the requirements. In this study, 9 patients benefitted from the long-term measurements at home. Successful therapy was based on a total of 3238 h of homely recorded ICP data (on average 359.8 h per patient). The multiple measurements before and after therapeutic interventions (valve adjustments or surgical revisions) led to specific in- and out-patient appointments to optimize the therapy. Case no. 2 illustrates the effectiveness of the mentioned approach. The patient required multiple measurements (total measuring time at home, 1536 h) and remote analyses ($n = 18$), but only 2 scheduled out-patient visits to get rid of the chronic headaches. It is inconceivable that similar therapy successes could be achieved with non-telemetric ICP probes or other conventional treatment regimen, such as repeated out-patient visits for "clinically oriented" valve adjustments [5].

Another prime example underlining the importance of home monitoring or home telemonitoring refers to neuro endoscopic interventions. The outcome of ETV is frequently uncertain and can be assessed in most cases after 4–6 weeks at the earliest [3, 4]. A total of 5 patients were monitored after endoscopy (Pat. ID 6, 17, 18, 19, 20). A regular postoperative ICP profile indicating ETV success could be observed in 4 cases while ETV failure became apparent in one case. However, the total measurement time at home counted to 1300 h (on average 260 h per patient). This very long observation period provided very high diagnostic and prognostic certainty regarding the postoperative outcome [3]. This kind of postoperative surveillance is only feasible due to telemetric and home monitoring/home telemonitoring technique.

Finally, it should be noted that the presented work only included patients who underwent the home telemonitoring ($n = 18$) or home monitoring ($n = 2$) process. Thus, a direct comparison to conventionally treated patients (e.g., no ICP measurements at all, usage of conventional non-telemetric ICP probes, and only measurements during in-patient stays) is not possible. Due to the purely descriptive character of this observational study, the advantages and benefits of the presented technique are only suggestive. Another crucial point concerns the question whether home monitoring or home telemonitoring should be applied. Both methods represent an advanced management of ICP measurement and hydrocephalus care. Furthermore, indications for both methods and patient selection criteria are equal. However, home telemonitoring is a special offer to the patients to extend the measurement process without additional obligations. Also, home telemonitoring is "customized" for those who live far away from specialized hospitals. Here, out-patient appointments can be limited to an absolutely necessary minimum.

In conclusion, the presented technique and its components provide potential advantages. First of all, telemetry of ICP is safe, valid, reliable, and of equal value in children and adults [4, 5, 14, 16, 17, 23]. Moreover, the long-term recording property is of huge clinical importance and tailored to the needs of the very complex cases [4]. Second, home monitoring enables "intracranial insights" under real everyday conditions [1, 4, 23]. This leads to new knowledge about the pathophysiology of hydrocephalic diseases and the influence of therapeutic approaches. Third, home telemonitoring of ICP is feasible, simple to establish, and solves the well-known problem of limited data storage [4]. The involvement of the patients in the whole process conveys the feeling of an active contribution to their convalescence. From an economic point of view, home telemonitoring can avoid unnecessary out-patient visits and hospitalizations. However, the main advantage of the presented technique is probably the possibility to treat patients living far away. In this way, medical care can be provided to those requiring special hydrocephalus clinics, irrespective of where they come from. Since the home telemonitoring setup can be used as a first diagnostic and follow-up tool, this could constitute a new way in hydrocephalus management.

Acknowledgments We wish to thank Mr. Rüdiger Koop (Saarland University Medical Center and Saarland University Faculty of Medicine, Homburg, Germany) for producing and processing the figures. We also thank Mr. Lukas Schary (Johannes Gutenberg University, Mainz, Germany) for revising and improving the language of this manuscript.

Compliance with ethical standards

Conflict of interest Sebastian Antes has received honorarium for speaking at symposia from the Raumedic AG, Helmbrechts, Germany. This relationship did not influence the results of the presented work. The authors finally declare that there have been no financial donations associated with this article.

Ethical approval For this type of study formal consent is not required.

References

1. Andresen M, Juhler M, Munch TN (2012) Quality and safety of home ICP monitoring compared with in-hospital monitoring. Acta Neurochir Suppl 113:187–191
2. Antes S, Tschan CA, Kunze G, Ewert L, Zimmer A, Halfmann A, Oertel J (2014) Clinical and radiological findings in long-term intracranial pressure monitoring. Acta Neurochir 156:1009–1019
3. Antes S, Tschan CA, Oertel JM (2014) An operative technique combining endoscopic third ventriculostomy and long-term ICP monitoring. Childs Nerv Syst 30:331–335
4. Antes S, Tschan CA, Heckelmann M, Breuskin D, Oertel J (2016) Telemetric intracranial pressure monitoring with the Raumedic Neurovent P-tel. World Neurosurg 91:133–148
5. Antes S, Stadie A, Müller S, Linsler S, Breuskin D, Oertel J (2018) Intracranial pressure-guided shunt valve adjustments with the Miethke sensor reservoir. World Neurosurg 109:e642–e650
6. Barber JM, Pringle CJ, Raffalli-Ebezant H, Pathmanaban O, Ramirez R, Kamaly-Asl ID (2017) Telemetric intra-cranial pressure monitoring: clinical and financial considerations. Br J Neurosurg 31:300–306
7. Bui AL, Fonarow GC (2012) Home monitoring for heart failure management. J Am Coll Cardiol 59:97–104
8. Cruz J, Brooks D, Marques A (2014) Home telemonitoring in COPD: a systematic review of methodologies and patients' adherence. Int J Med Inform 83:249–263
9. Czosnyka M, Pickard JD (2004) Monitoring and interpretation of intracranial pressure. J Neurol Neurosurg Psychiatry 75:813–821
10. Eide PK, Brean A (2006) Intracranial pulse pressure amplitude levels determined during preoperative assessment of subjects with possible idiopathic normal pressure hydrocephalus. Acta Neurochir 148:1151–1156
11. Eide PK, Sorteberg W (2010) Diagnostic intracranial pressure monitoring and surgical management in idiopathic normal pressure hydrocephalus: a 6-year review of 214 patients. Neurosurgery 66:80–91
12. Ertl P, Hermann EJ, Heissler HE, Krauss JK (2017) Telemetric intracranial pressure recording via a shunt system integrated sensor: a safety and feasibility study. J Neurol Surg A Cent Eur Neurosurg 78:572–575
13. Fouyas IP, Casey AT, Thompson D, Harkness WF, Hayward RD (1996) Use of intracranial pressure monitoring in the management of childhood hydrocephalus and shunt-related problems. Neurosurgery 38:726–731
14. Freimann FB, Schulz M, Haberl H, Thomale UW (2014) Feasibility of telemetric ICP-guided valve adjustments for complex shunt therapy. Childs Nerv Syst 30:689–697
15. Kew KM, Cates CJ Home telemonitoring and remote feedback between clinic visits for asthma. Cochrane Database Syst Rev 8: CD011714
16. Kiefer M, Antes S, Leonhardt S, Schmitt M, Orakcioglu B, Sakowitz OW, Eymann R (2012) Telemetric ICP measurements with the first CE-approved device: data from animal experiments and initial clinical experiences. Acta Neurochir Suppl 114:111–116
17. Lilja A, Andresen M, Hadi A, Christoffersen D, Juhler M (2014) Clinical experience with telemetric intracranial pressure monitoring in a Danish neurosurgical center. Clin Neurol Neurosurg 120:36–40
18. Maeske M, Mayer S, Blanc SM, Schulz C, Kunz U, Mauer UM (2016) Telemetric intracranial pressure measurement: a graphical approach to data analysis. J Neurol Surg A Cent Eur Neurosurg 77:258–263
19. Paré G, Jaana M, Sicotte C (2007) Systematic review of home telemonitoring for chronic diseases: the evidence base. J Am Med Inform Assoc 14:269–277

20. Paré G, Moqadem K, Pineau G, St-Hilaire C (2010) Clinical effects of home telemonitoring in the context of diabetes, asthma, heart failure and hypertension: a systemic review. J Med Internet Res 12:e21
21. Schuhmann MU, Sood S, McAllister JP, Jaeger M, Ham SD, Czosnyka Z, Czosnyka M (2008) Value of overnight monitoring of intracranial pressure in hydrocephalic children. Pediatr Neurosurg 44:269–279
22. Weerakkody RA, Czosnyka M, Schuhmann MU, Schmidt E, Keong N, Santarius T, Pickard JD, Czosnyka Z (2011) Clinical assessment of cerebrospinal fluid dynamics in hydrocephalus. Guide to interpretation based on observational study. Acta Neurol Scand 124:85–98
23. Welschehold S, Schmalhausen E, Dodier P, Vulcu S, Oertel J, Wagner W, Tschan CA (2012) First clinical results with a new telemetric intracranial pressure-monitoring system. Neurosurgery 70:44–49

Comments

The study by Tschan et al. describes a new method for long-term telemetric ICP monitoring through videolink consultations with online analysis of ICP data acquired in the patient's home ("home telemonitoring"). This way of managing patients with (suspected) hydrocephalus is interesting, at least when patients live far away from the neurosurgical unit. However, actual "telemedicine" requires treatment actions to be taken from the distance, which is not the case at the moment, meaning that patients need to visit the neurosurgical unit if ICP is abnormal, e.g., for changes in shunt valve setting. Another issue at the moment is the high cost of the available telemetric reading device, making it unlikely that each patient can be supplied with one.

This method of management have a narrow use at the moment, but if adjustable shunt valves can be adjusted online in the future and telemetric reading devices can be supplied with each sensor, the idea of home telemonitoring of ICP might gain more attention.

Alexander Lilja-Cyron
Copenhagen, Denmark