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Case Study of Relevant Pressures for an Implanted Hydrocephalus Valve in Everyday Life*

Inga Margrit Elixmann[1], Christine Goffin[1], Rolf Krueger[2], Ullrich Meier[3], Johannes Lemcke[3], Michael Kiefer[4], Sebastian Antes[4] and Steffen Leonhardt[1], *Senior Member, IEEE*

Abstract— **Hydrocephalus patients with increased intracranial pressure are generally treated by draining cerebrospinal fluid (CSF) into the abdomen through an implanted shunt with a passive differential pressure valve. To perfectly adapt the valve's opening pressure to the patient's need, more information on the acutal pressure across the valve in everyday life actions like walking, eating, sleeping etc. is necessary.**
Therefore, intracranial pressure (ICP), intra-abdominal pressure (IAP) and the hydrostatic pressure between both ends of the the fictitious shunt have been measured simultaneously for up to 24 hours in home environment at different body postures. The patient was wearing the new telemetric ICP probe Neurovent-P-tel as implant. The pressure sensor Omnibar E5F measured IAP in the rectum (10 cm deep).
In this pilot study, IAP increased 20 mmHg more than ICP during coughing and 35 mmHg more during sneezing. As the pressure difference across the fictitious valve became negative in some postures, CSF drainage would not have been possible. To the authors' knowledge, this is the first paper that presents measurements, which provide insight into the differential pressure across a hydrocephalus valve in everyday life and give information for future electromechanic shunts development.

I. Introduction

The human brain is sourrounded by cerebrospinal fluid (CSF), which protects the brain from hard impacts and provides buoyancy. CSF is renewed in average by around 20 ml per hour. In hydrocephalus patients more CSF can be produced than reabsorbed and beeing surrounded by a rigid skull, the increased amount of CSF causes an intracranial pressure (ICP) rise. Hydrocephalus patients are genereally treated by implanting a shunt to drain excess fluid (s. Fig. 1). A burr hole is drilled into the cranium, and the shunt catheter is placed into the CSF space. A valve is attached to the catheter at one end, at its other end it is connected to a silicon tube which passes underneath the skin and drains the excessive CSF into a different body compartment - preferably the abdomen. There the CSF is absorbed.

CSF is drained, whenever the pressure difference across the implanted valve exceeds its opening pressure. Up to now simply mechanical valves are in use. The disadvantage of mechanical valves is that they cannot automatically adapt to altered conditions or control according to a desired therapy plan over time. Additionally the physician cannot tell whether the right ICP develops without employing invasive or costly imaging techniques. Therefore an electromechanic shunt must be the future goal for a better hydrocephalus therapy.

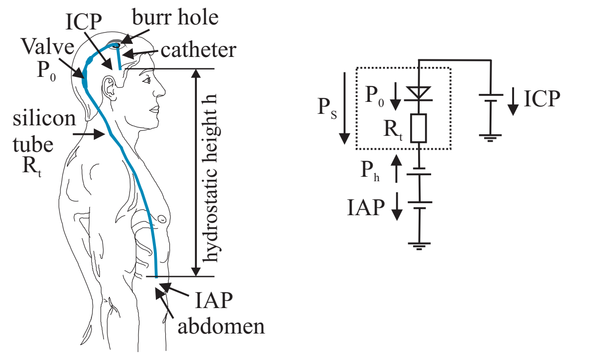

Fig. 1. Implanted shunt for hydrocephalus therapy and equivalent circuit diagramm, with the tube resistor R_t, the opening pressure of the valve P_0, the differential pressure across the shunt P_S and the hydrostatic pressure P_h

One important step towards an electromechanic shunt is the development of a longtime stable telemetric ICP sensor. In 2010, for the first time a telemetric pressure sensor (s. Fig. 2) obtained a CE-mark for longterm monitoring of ICP [1]. During the evaluation within an animal experiment of up to 18 months, some of the sensors had a zero drift but the amplitude was measured correctly all the time [2]. Welschehold et al. presented first clincial results of the ICP measurents with patients of up to 180 days and did not measure any zero drift [3].

Another important step towards an electromechanic shunt is to measure the intra-abdominal pressure (IAP), the ICP and the hydrostatic pressure in the silicon tube at the same time during natural body movements in order to determine the differential pressure along the shunt at each body posture. Coughing, sneezing and a change in body posture affects IAP and ICP. Posture changes have already been investigated by elevating the head of the bed during IAP [4] and during ICP measurements [5]. Grillner et al. observed the change in IAP during walking [6] and Cobb et al. extended these measurements to further natural movements [7]. Changes in ICP due to natural movements or measurements of IAP and ICP at the same time have not been published

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[1]I. M. Elixmann, C. Goffin, S. Leonhardt are with the Helmholtz Institute for Biomedical Engineering, RWTH Aachen University, Aachen, Germany
[2]R. Krueger works at Hitec-Zang GmbH, Herzogenrath, Germany and is affiliated member of Helmholtz Institute for Biomedical Engineering, RWTH Aachen University, Aachen, Germany
[3]U. Meier and J. Lemcke are with the Department of Neurosurgery, Unfallkrankenhaus Berlin, Berlin, Germany
[4]M. Kiefer and S. Antes are with the Department of Neurosurgery, Saarland University, Homburg, Germany

yet. With the new telemetric ICP sensor, new insight can be gained for the development of an ideal hydrocephalus shunt. To know how a passive shunt reacts and how to control a future electromechanic shunt, it is important to evaluate the resulting differential pressure over the shunt in different everyday life situations. What is the optimal opening pressure for a valve for different body postures? Does overdrainage occur during sneezing or coughing? These questions are addressed by this case study. This paper firstly presents measurements of ICP during different actions over whole day and night, then IAP measurements occuring at different body postures and finally measurements of IAP, ICP and hydrostatic pressure at the same time and thus the resulting pressure over a fictitious hydrocephalus valve.

II. Methods

In this study the ICP of one patient (56 years old, male, 183 cm tall with a body mass index of 32) with an implanted telemetric ICP sensor was monitored at home. Up to three pressure values were continuously measured (the telemetric ICP at 5 Hz, the other pressures at 100 Hz) for up to 24 hours by the mobile monitor device Datalogger and pressure sensors of Raumedic, Germany. An Omnibar E5F pressure sensor was used for IAP measurements (10 cm deep into the rectum), the implanted Neurovent-P-tel probe (s. Fig. 2) was used to measure intracranial pressure and the Neurovent-P pressure sensor was used for hydrostatic pressure measurements. The hydrostatic pressure sensor was integrated at the bottom of an open-top silicon tube with 3 mm inner diameter to measure the hydrostatic pressure of a fictitious shunt. This water-filled tube was attached at the patients back. Its lower end was attached at the same height as the IAP sensor in the rectum and the higher end at the height of the telemetric ICP sensor in the head.

The test subjects journalized their movements for all three experiments. The explanted telemetric ICP probe was verified at the end.

In a first experiment, intracranial pressure was measured during daily routine, in a second experiment the IAP was measured for different postures and compared with a second slimmer and younger male person (34 years old, 172 cm tall with a body mass index 24). In the third experiment ICP, IAP and hydrostatic pressure has been measured simultaneously to determine the resulting pressure which would occur across a hydrocephalus shunt valve.

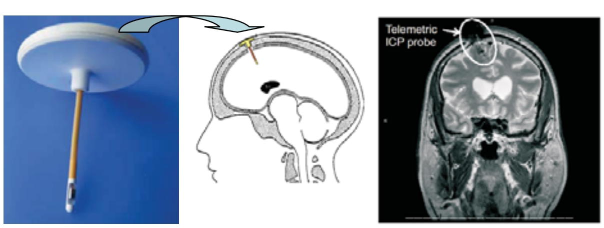

Fig. 2. Supposed placement of telemetric intracranial pressure sensor Neurovent-P-tel within the cranium and magnetic resonance image (coronal/frontal plane, T2) of the patient with this sensor

III. Results and Evaluation

A. Intracranial Pressure during Daily Routine

The ICP over a whole day and night has been measured continuously and the result can be seen in Fig. 3. It can be observed that ICP changes from -9 to +9 mmHg when changing the posture from standing or sitting to lying down. Pressure peaks arise due to abrupt movements like sitting down or due to coughing or pressing during bowel movement.

The explanted telemetric ICP probe deviated less than 2 mmHg from the correct value in the ICP range from 0 to 20 mmHg and had a drift of less than 1.5 mmHg. Fig. 2 shows the magnet resonance image of the telemetric ICP probe within the patient.

B. Intra-Abdominal Pressure for Different Postures

In this second experiment, test subjects stay in typical everyday life postures for around 60 seconds while IAP is measured continuously (s. Fig. 4). To make first estimates about the differential pressure across the valve, a desired ICP (-7 mmHg for an upright body position, 7 mmHg for a supine position) and a hydrostatic pressure P_h (60 cm depth of water for an upright body position, 0 cm for a supine position) have been assumed and plotted in Fig. 4. The differential pressure P_S along the shunt can be calculated as follows (see the equivalent circuit diagramm in Fig. 1)

$$P_S = ICP + P_h - IAP. \quad (1)$$

Draining is possible when $P_s > 0$ and the target volume flow $\dot{V}_{target}$ through the shunt in the case of positive differential pressure can be controlled by adjusting the valve's opening pressure P_0 as follows

$$P_0 = P_S - R_t \cdot \dot{V}_{target} \quad (2)$$

with R_t being the tube resistance. These quasi-static measurements of IAP reveal, that the valve can only definitely drain to the physiological target ICP, when the patient (BMI 32) is sitting. Draining CSF is also possible, when standing or lying on the side if the patient's abdomen is relaxed, which means that the patient do not suffer for example from flatulence. Comparing the patient with the reference person (BMI 24), it becomes evident that optimal drainage body postures are depending on the individual.

Compared with literature, the IAP values of the relaxed patient with the telemetric implant (BMI 32) are 10 mmHg higher than found by Cobb et al. [7] for obese subjects. However, the changes of IAP when changing posture to sitting and standing are the same.

C. Measurement of Resulting Pressures across a Hydrocephalus Shunt

Intracranial pressure and intra-abdominal pressure were measured in this third experiment at the same time with the hydrostatic pressure for 16 h including daytime and one night (s. Fig. 5 and 6). The topmost subgraph displays the

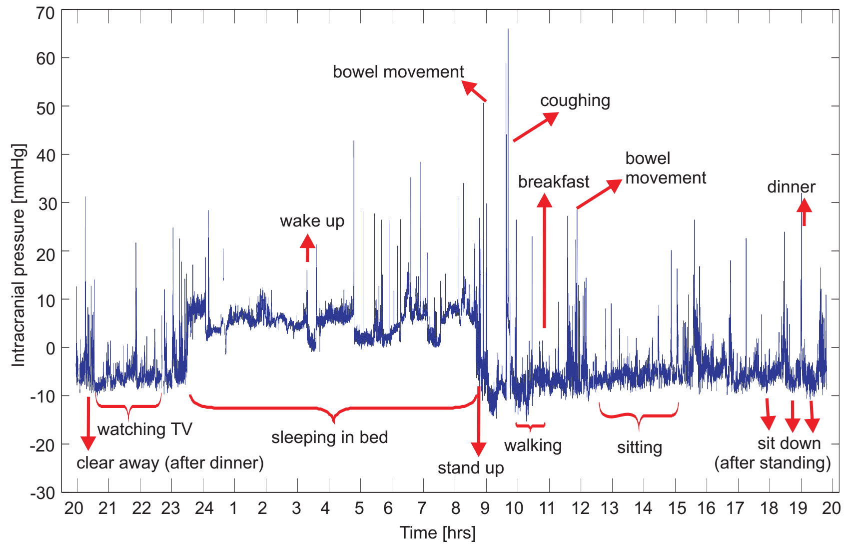

Fig. 3. Intracranial pressure course over 24h daily routine at home

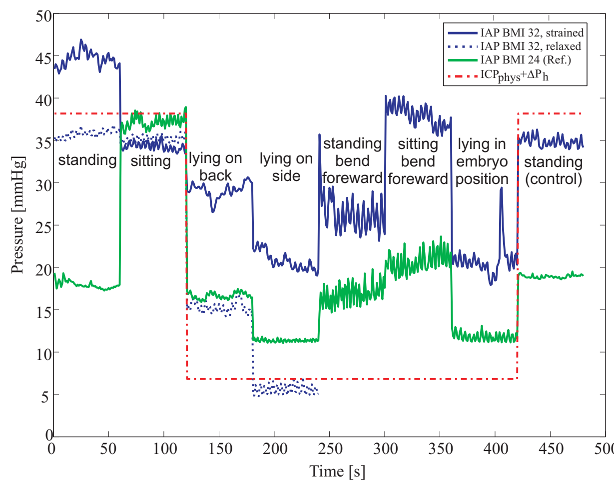

Fig. 4. Measurement of intra-abdominal pressure at different body posture of two persons with different body mass indices (BMI) compared with physiolocial ICP (ICP_{phys}) and hydraulic pressure changes (ΔP_h) typical for each posture

intra-abdominal and intracranial presure course, the second subgraph the hydrostatic pressure with the annotated body posture and the lowermost subgraph shows the calculated resulting differential pressure P_v over the valve. During daytime, body posture was journalized constantly by the patient.

The intracranial pressure changes according to the the body posture. The dynamic IAP values fit to the quasi-static values measured in the section III-B of the strained test subject with BMI 32, except for sitting (here values from sitting are similar to the ones of standing). Over night while lying on the left side, the IAP is reduced to the smallest value of around 9 mmHg with small amplitudes of 1 mmHg. However there are some big peaks up to 75 mmHg for example at 0:34 a.m. and 1:11 a.m.. The authors suppose, that these peaks arise from peristaltic movements. Due to muscle movements in the rectum, the measured pressure doesn't equal the IAP at this moment.

As expected by the results from section III-B, during night-time when lying on the side, the differential pressure is positive. In other postures, the average of P_S of each hour can get to -20 mmHg. The patient did have a physiological ICP values during these measurements, but an increase of 20 mmHg in ICP would not be advisable. It needs to be evaluated, if pressure peaks from movements inducing values of P_S greater than zero are sufficient for drainage.

From the measurements, it can be deduced that the differential pressure P_S decreases when coughing or sneezing (s. Fig. 7 and table I). The value of IAP rise when coughing matches to the value measured by Cobb et al. [7]. The amplitude in IAP due to walking was around 11 mmHg in our measurements, which was the same as measured by Grillner et al. [6] for a walking speed of 6 km/h.

TABLE I

MEASURED PRESSURE DIFFERENCES DURING COUGHING AND SNEEZING

	ΔICP [mmHg]	ΔIAP [mmHg]	ΔICP- ΔIAP [mmHg]
Coughing	40	60	-20
Sneezing	35	60	-35

IV. Conclusion and Outlook

This paper gives an insight into the dynamic behaviour of intracranial and intrabdominal pressure. Although only examplarily with one patient, this paper highlights the importance of the IAP for the differential pressure of the shunt. With the new possiblity to measure intracranial pressure by an implant, we conclude, that coughing and sneezing may not lead to overdrainage because the intra-abdominal pressure

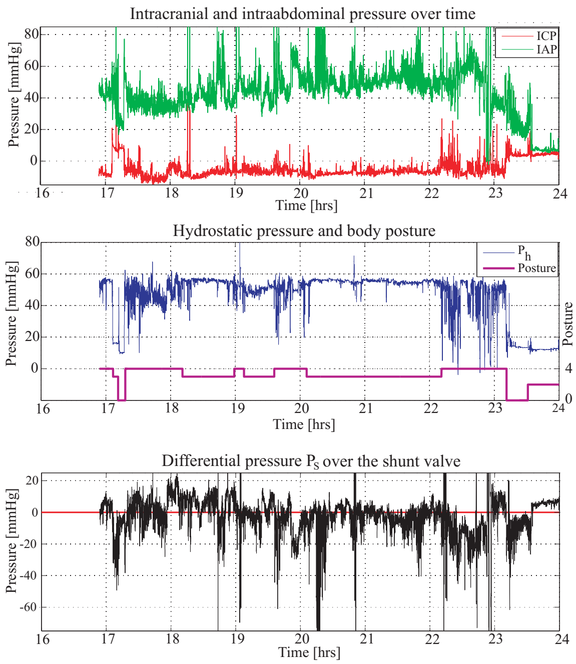

Fig. 5. Afternoon and Evening: Measured intracranial, intra-abdominal and hydrostatic pressure, calculated differential pressure over the valve and body posture (0:lying on the back, 1:lying on the right side, 2:lying on the left side, 3:sitting, 4:standing or walking)

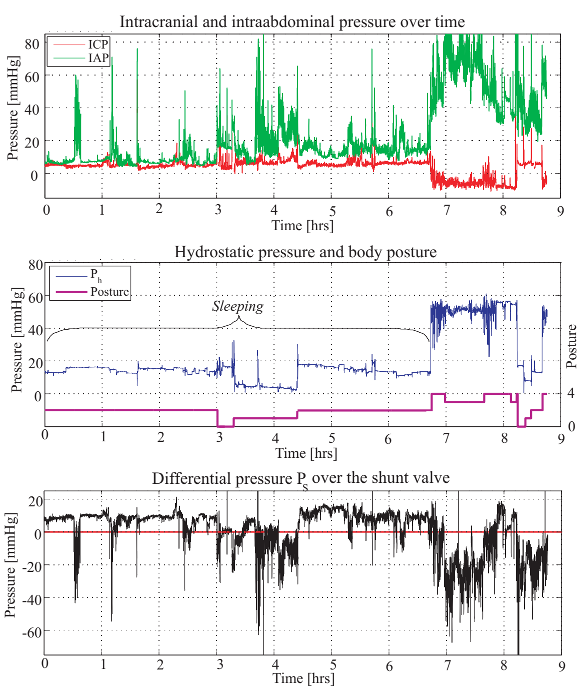

Fig. 6. Night and Morning: Measured intracranial, intra-abdominal and hydrostatic pressure, calculated differential pressure over the valve and body posture (0:lying on the back, 1:lying on the right side, 2:lying on the left side, 3:sitting, 4:standing or walking)

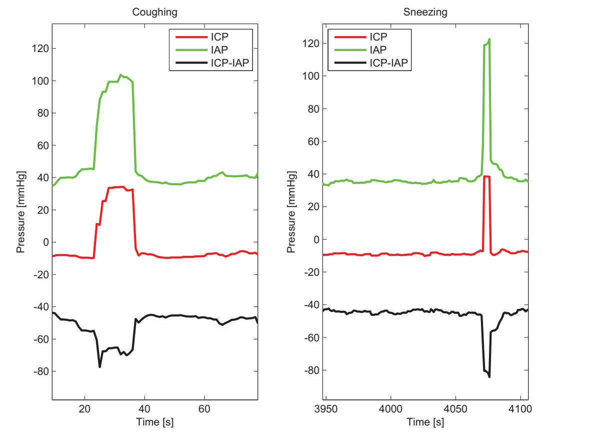

Fig. 7. ICP, IAP and the difference in the moment of coughing and sneezing

seems to increase more than the intracranial pressure. Hence there is no need to increase the valve's opening pressure for these pressure peaks. Depending on the patient and its strain on the abdomen, a valve relying upon the differential pressure might not drain cerebrospinal fluid in all body postures. A future electromechanic valve can measure the differential pressure. When this pressure is negative, it can give feedback to the patient to change the body posture. A different solution to be independent of the differential pressure would be to use a pump to drain cerebrospinal fluid, but energy consumption needs to be evaluated. As this was a case study, it is important to verify in future studies, if these results can be generalized.

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