Electrostatic discharges and their effect on the validity of registered values in intracranial pressure monitors

Laboratory investigation

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Object. Intracranial pressure (ICP) monitoring is used extensively in clinical practice, and as such, the accuracy of registered ICP values is paramount. Clinical observations of nonphysiological changes in ICP have called into question the accuracy of registered ICP values. Subsequently, the authors have tried to determine if the ICP monitors from major manufacturers were affected by electrostatic discharges (ESDs), if the changes were permanent or transient in nature, and if the changes were modified by the addition of different electrical appliances normally used in the neurointensive care unit environment.

Methods. The authors established a test setup in the neurointensive care unit using a large container filled with isotonic saline, creating a phantom patient. Intracranial pressure monitors were sequentially lowered into the container and subjected to a predefined test battery of ESDs.

Results. Five pressure monitors from 4 manufacturers were evaluated. Three monitors containing electrical circuitry at the tip of the transducer were all affected by ESDs. Clinically significant permanent changes in the reported ICP values for 1 pressure monitor were observed, as well as temporary deflections for 2 other monitors. The monitors had different levels of sensitivity to discharges at low voltages.

Conclusions. These results explain some of the sudden shifts in ICP noted in the clinical setting. However, a clear deflection pattern related to the addition of electrical appliances was not found. The authors recommend instituting policies for reducing the risk of subjecting patients to ESDs in the neurointensive care unit setting.

(http://thejns.org/doi/abs/10.3171/2013.7.JNS13506)

Key Words • intracranial pressure monitoring • electrostatic discharge • functional neurosurgery
cal susceptibility are not as well known. Consequently, in this paper, the questions—and the scientific methods used to answer them—may appear foreign to the reader, but the consequences are highly patient-centered when technical errors cause clinical misjudgment. Accordingly, the methods and results in this paper are of a rather technical nature, while the following discussion and conclusions have a clinical focus with recommendations on handling the issues that we describe.

Methods

Testing Procedure

We established a test setup in a patient room in the neurointensive care unit at our hospital. The room was fully fitted with the standard equipment that is regularly used for patient monitoring, and as such resembles the “real world” conditions that the tested equipment is required to be able to operate under.

At the center of the room we placed an adjustable patient bed with an electrically powered pressure-relieving mattress (Fig. 1). In the bed, two $80 \times 60 \times 20$-cm containers were placed, filled with isotonic saline, and connected with a soaked towel, to simulate a patient. The total volume of water was 40 L. The ICP pressure monitors included for evaluation had not been used previously, were used exclusively for this study, and were tested before their date of expiry. The pressure monitors were sequentially lowered into the container with the transducer $5$ mm under the water surface.

Prior to performing the experiment, we selected a number of “challenges” to the ICP pressure monitors to determine their resilience to ESDs when different types of electrical equipment were added to the setup surrounding our phantom patient. Sequentially, we added a patient bed, an electrically powered pressure-relieving mattress, ECG cables and pulse oximetry monitor, and finally an infusion pump.

Each electrical appliance was added in addition to the previous items on the list. At each “challenge level” we performed 5 sequential ESDs, with the tip of an ESD generator (air and contact discharge; Type ESD 30, P18 and P30, EM Test) submerged in the water, to test the ICP pressure monitors. The monitors were subjected to discharges of $0$, $\pm 2$, $\pm 4$, and $\pm 8$ kV. With 4 challenge levels and 7 discharge levels, we gathered 28 individual recordings from each ICP monitor. These recordings can be thought of as 28 specific scenarios that might feasibly arise in a normal neurointensive care unit.

Testing Assessment

During each test we noted the starting and ending baseline, defined as the modal value of the first and last second of the recording, respectively. Additionally, we noted the maximum deflection from the baseline in millimeter of mercury (mm Hg), as well as the duration of the deflection in seconds. This duration value was subdivided into a pre- and postpeak phase to determine if there was a recovery period following the ESDs. Data were processed using the R statistical software package.

The electrostatic environment in the room was continuously monitored using a field mill. As an electrostatic voltmeter, it measures surface voltages and makes continuous recording of the direct current potential possible. The field mill was repeatedly used for checking that the electrostatic potential in the test area did not build up due to triboelectric charges from moving materials in the vicinity of the test area or from charges from test personnel moving around the setup. Triboelectric charging can result from rubbing different materials such as packaging material, plastic, rubber, clothing, non-ESD footwear, or other sources against each other. It was concluded that the setup was not subject to unintentional build-up due to static charging sources. The intentional ESD generator was the only source of electrostatic charging. This technical step is important for verification of the experimental setup, and

Fig. 1. The experimental setup at the neurointensive care unit. A “phantom patient” consisting of 2 saline-filled containers was placed in a patient bed. Each test consisted of 3 parts as shown in the figure. Each ICP monitor was lowered into the saline-filled container (1), and for each challenge (2), ESDs were performed (3) at $0$, $\pm 2$, $\pm 4$, and $\pm 8$ kV.
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ensures that the delivered ESDs are accurate, reproducible, and not affected by other factors in the room.

**Results**

Five pressure monitors were selected for evaluation: 1) a fluid-filled transducer (Edwards TruWave), 2) the Codman MicroSensor, 3) Raumedic Neurovent-P (cable monitor), 4) Raumedic Neurovent-P-tel (telemetric monitor), and 5) Integra Camino MPM-1. The maximum deflection of ICP (mm Hg) from the starting baseline is summarized in Fig. 2. Of note, the fluid-filled transducer and the Camino monitor were the only monitors not affected by ESDs. However, as they operate based on fluid pressure and a fiber optic cable, respectively, this was as expected. The remaining 3 monitors have electrical components at the tip of the transducer for conversion of the pressure signal, and all were affected by ESDs. When investigating the affected ICP monitors, the polarity of the applied voltage affected the direction of the deflection, with positive polarity primarily causing a positive deflection, and vice versa. Additionally, the effect of positive voltages on the ICP deflection was larger than negative voltages in our experimental setup.

When examining differences in the starting and ending baseline, only the Codman MicroSensor displayed such changes (Fig. 3). All other monitors showed returned to the starting baseline after brief spikes (Fig. 4), with variations in the duration of deflections (Fig. 5). The Neurovent-P-tel telemetric pressure monitor frequently lost the signal when the discharges were performed, displaying an error message on the ICP monitor. While it is clearly unsatisfactory to lose the signal at even small discharge levels, arguably it is better to lose the signal for a short period than to receive false ICP values.

The Codman MicroSensor was shown to be more resilient to low levels of ESDs than the 2 Raumedic devices. However, at higher discharge levels, the baseline measured by the MicroSensor was permanently displaced up to 39 mm Hg after the series of 5 sequential discharges (Fig. 7). When used in the clinical setting at our institution, the ICP data from the Codman MicroSensor is relayed to a wall-mounted computer screen displaying a graphical representation of the waveform. Using the built-in trend function, historical data can be reviewed. However, to avoid acting on technically invalid data, care providers need to be qualified to perform a more careful evaluation of the pressure signal, and consider reviewing historical data to detect nonphysiological sudden shifts in ICP. The poten-

**Discussion**

*Differences Between Tested Pressure Monitors*

For reasons of patient safety, the reliability and accuracy of measured ICP values are essential. However, we report marked differences between different types of ICP monitors tested in a standardized setting in their abilities to handle ESDs at levels that are both possible and likely in the clinical setting. It is not possible to provide standard values for the voltage levels produced by common bedside actions, but Table 1 describes electrostatic charge voltages observed in 4 different standard ESD environments. These values highlight how common the tested voltages are likely to be in a neurointensive care unit.

The Raumedic Neurovent-P displayed the largest sudden shifts in the registered pressure signal, as well as changes induced at the lowest discharge levels. However, coupled with the short duration of less than a second before returning to the starting baseline, the appearance of these artifacts are decidedly nonphysiological, and in our opinion would not give rise to any clinical misinterpretation and unnecessary intervention.

Like its cable-based sibling, the telemetric Raumedic Neurovent-P-tel was easily affected, but instead of short deflections, the telemetric pressure monitor lost the signal for up to 20 seconds while displaying an error message on the ICP monitor. While it is clearly unsatisfactory to lose the signal at even small discharge levels, arguably it is better to lose the signal for a short period than to receive false ICP values.

The Codman MicroSensor was shown to be more resistant to low levels of ESDs than the 2 Raumedic devices. However, at higher discharge levels, the baseline measured by the MicroSensor was permanently displaced up to 39 mm Hg after the series of 5 sequential discharges (Fig. 7). When used in the clinical setting at our institution, the ICP data from the Codman MicroSensor is relayed to a wall-mounted computer screen displaying a graphical representation of the waveform. Using the built-in trend function, historical data can be reviewed. However, to avoid acting on technically invalid data, care providers need to be qualified to perform a more careful evaluation of the pressure signal, and consider reviewing historical data to detect nonphysiological sudden shifts in ICP. The poten-
tional problem becomes worse if ICP data are exclusively read from the accompanying “ICP Express” monitoring unit, which only displays the current ICP value, with no capabilities for reviewing historical data. In these cases it is impossible to determine from the device if a new higher ICP value is a result of gradual physiological changes in ICP over time or a sudden shift as a result of ESDs.

Validity of Obtained Pressure Signals

At present, our suggestion for verification of the validity of the obtained ICP data is to review the pulse amplitude of the ICP signal. At higher ICP values, the amplitude should increase correspondingly. Identical pulse amplitudes, but with a difference of 20 mm Hg in the static pressure signal, is an indicator that the measured ICP value cannot be taken at face value.

To verify our results, we repeated the test of the Codman MicroSensor immediately after the first run. The ± 8-kV test was skipped in some test configurations to minimize the number of damaged sensors. The ICP value continued to rise from 42 mm Hg in the first test to about 100 mm Hg, at which point the sensor malfunctioned and was no longer able to provide a signal. We then repeated the test with another MicroSensor catheter, with similar results. Both catheters were connected to the ICP Express monitor again after a week, but were still not able to function.

Our results support the results from Eide and Bakken who performed ESDs in a small saline-filled container in a bench test, testing the reliability of the Codman MicroSensor and the Raumedic Neurovent-P, Neurovent-P-C, and Neurodur pressure monitors. Testing a total of 57 explanted pressure monitors, they found alterations exceeding 2 mm Hg in measured baseline pressure in almost all Codman monitors and in about half of the tested Raumedic monitors. They reported gradual shifts in the ICP baseline for 2 MicroSensor monitors, and for the remaining monitors, sudden shifts comparable with the results from our test. For the Neurovent-P pressure monitor, the majority of tested monitors did not show any permanent shifts in baseline ICP, but a single pressure monitor showed a permanent shift of 10 mm Hg. It is unclear at which discharge levels Eide and Bakken observed the sudden shifts for each pressure monitor, but the fact that clinically significant changes in the ICP baseline were noted in both experiments highlights the importance of the observations. Additionally, the results from our study—when testing brand new pressure monitors—make it highly unlikely that the results from Eide and Bakken were caused by damage to the pressure monitors during insertion or explantation.

Sudden Versus Gradual Drift

Based on our results, it is now possible to explain some of the sudden shifts in ICP observed in the clinical setting. We did not observe gradual shifts, which we have observed clinically in the neurointensive care unit setting. Either the mechanism is different from what we have shown, or the gradual shifts are, in fact, a myriad of small individual discharges, slowly accumulating to result in clinically significant changes. Eide and Bakken demonstrated gradual drifts in a few of their tested pressure monitors following ESDs, but the basis for this mechanism remains unclear. The next step in determining this technical error could be to evaluate the effect of electromagnetic fields on the same group of ICP monitors or to expand the experimental setup that we have described in this paper. This could be in the form of a long-term study of ICP monitors in an electrically noisy “real world” envi-
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Our test included 5 different types of ICP monitors and was performed in a clinical setting with sequential addition of electronic neurointensive care unit equipment to identity potential specific causes of ESDs. We did not find a clear pattern in increasing levels of deflection with the addition of electrical equipment—rather, in several of the tests the challenge level with the most appliances caused the smallest deflections in ICP. It is unclear whether these appliances might provide a dissipation route in some cases.

Until we are able to further document the technical changes in reported ICP values caused by different types of electrical interference, we would recommend instituting policies for reducing the risk of subjecting patients to ESDs in the neurointensive care unit setting. Ideally, this would take place in the form of “grounding” patients, physicians, as well as electrical equipment with electrostatic bracelets, which are also used in the manufacturing industry when handling sensitive electronic components. This ensures that all interacting persons and equipment have an electrostatic potential of zero volts. As a stopgap measure it is possible to introduce grounded plates that the physician can stand on while interacting with the grounded patient; however, this approach requires the physician to be using footwear, which is not electrically isolated. Additionally, the relative humidity in the neurointensive care ward should be monitored and regulated to ensure values above 50–70%, at which point water molecules on the surfaces of equipment, patients, and physicians provide a weak path of dissipation for the ESDs. This last step causes the least inconvenience to clinicians working at the bedside, whereas electrostatic bracelets, with a cable connecting the physician to the wall, inhibit movement and interaction with the patient.

![Graph of the calculated ratio between pre- and postpeak deflection durations for the 3 monitors with deflections. The postpeak phase is longer for most measurements, indicating a small recovery period following discharges. The calculated ratio is a possible candidate for computer-assisted validation of the ICP signal.](image-url)
Conclusions

The 3 monitors containing electrical circuitry at the tip of the transducer were all affected by ESDs. The type of changes varied between the Codman and Raumedic pressure monitors. Discharges at low voltages caused more pronounced but transient signal changes in the Raumedic monitors. Permanent changes occurred in the measured signal values for the Codman pressure monitor. We recommend instituting policies for reducing the risk of subjecting patients to ESDs.

Disclosure


Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Acquisition of data: Andresen. Analysis and interpretation of data: all authors. Drafting the article: Andresen. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Andresen. Statistical analysis: Andresen.

Acknowledgment

The authors wish to acknowledge the help of Per Thåstrup Jensen from the engineering company Delta A/S for invaluable assistance in performing the technical measurements used in this study.

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Manuscript submitted March 26, 2013. Accepted July 22, 2013. Please include this information when citing this paper: published online August 23, 2013; DOI: 10.3171/2013.7.JNS13506.

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