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Simulation system for intraoperative neuromonitoring

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Abstract: This paper presents a simulation system ("patient model") for intraoperative neuromonitoring (IONM) applied to mastoidectomy. IONM is an electrophysiological method for monitoring the integrity and localization of nerve tracts, which helps the surgeon to avoid injuries and damage to neural risk structures (e.g. facial nerve) during surgery. To use the IONM successfully, the surgeon needs appropriate training and experience. The presented simulation system provides training possibilities in a realistic, cost-efficient and reproducible way.

In the simulation system, the position of the probe during training is determined by a magnetic tracking method. Depending on the distance to the virtual nerve, a synthetic electromyogram (EMG) signal is sent to a real neuromonitor. The trainee learns to interpret the output of the neuromonitor. The trainer can choose different training scenarios, such as localization of the nerve, milling or coagulating, using a web application.

Keywords: neuromonitoring, simulation system, ENT surgery, magnetic tracking, localization of nerve tracts

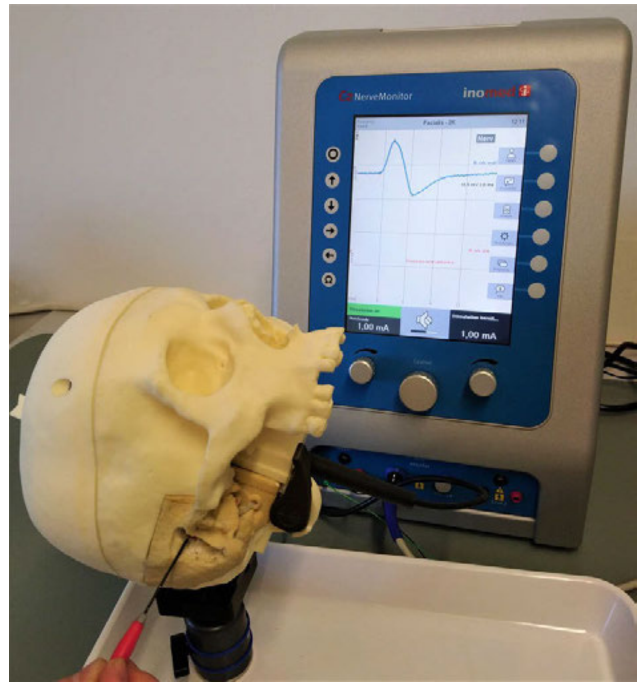

Fig. 1: Simulation system with Neuromonitor

1 Introduction

Due to the complex anatomy and numerous standard variations, petrosal surgery, as a special field of Ear, Nose, Throat (ENT) surgery, is one of the greatest challenges of skull base surgery. For complex and risky operations on the temporal bone intraoperative neuromonitoring has become established. This is an electrophysiological procedure for monitoring the integrity of nerves and locating nerve tracts, which actively supports the surgeon in avoiding iatrogenic injuries and damage to neural risk structures, such as the facial nerve and the chorda tympani, when milling the bone. The nerve in the situs is specifically electrically stimulated and an EMG of the energized muscle is derived.

The interpretation of the neurophysiological information supplied by the IONM device is a complex task that requires extensive experience of the surgeon [1]. To learn and refine the surgical procedures, temporal bone preparations are used, which are only available to a limited extent, are not reproducible and therefore difficult to objectify. Since the neural tissue is no longer biologically active, the IONM cannot be trained on preparations. The training on simulation models, which has been introduced in the training of surgeons for some time, is a risk-free and cost-effective method of gaining experience [2–4].

Existing simple IONM simulators or demonstrators reproduce the nerve tracts in the anatomical model by means of electrically conductive structures. If the stimulation probe comes into contact with the nerve tract, an EMG signal is generated and output to the neuromonitor. The EMG signal does not depend on the contact position, which is not very realistic. In contrast, the simulation system presented here (see Fig. 1) uses a contact free tracking method, which determines the position of the probe and its distance to the nerve tract. The location of the nerve tracts is stored in the system software and is not necessarily linked to a physical realization. Depending on position and distance, the EMG signal can therefore be generated in such a way that the output of the neuromonitor largely corresponds to that in the real application. With this simulation system the education and training of surgeons is more re-

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alistic and at the same time more effective, reproducible and cost-efficient. The training system enables the surgeon to use the potential of IONM, a modern, technically advanced procedure, optimally and comprehensively for the patient.

2 Materials and Methods

2.1 Overview of the simulation system

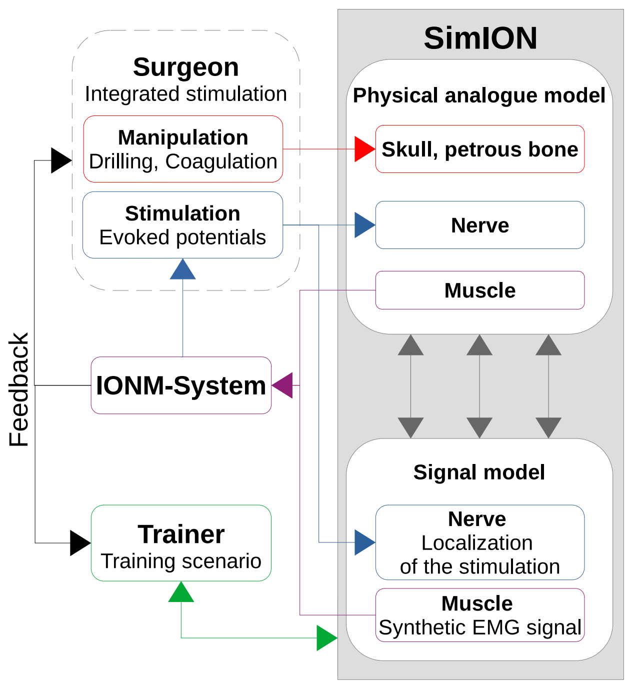

Fig. 2: Schematic structure of the SimION model

The so-called SimION system essentially consists of an anatomy model equipped with the sensor electronics for position measurement and a microcontroller-based processing unit used for position calculation and generation of the EMG signal. It is equipped with an interface to the neuromonitor and to a mobile device as HMI, see Fig. 2. The C2 NerveMonitor which is used in the SimION system is provided by inomed GmbH. Localization of the stimulation probe in the exercise anatomy is based on a non-contact tracking method using Hall effect sensors and a permanent magnet on the tip of the probe. Depending on the position of the probe and its distance to the virtual nerve, a synthetic EMG signal is generated and sent to the neuromonitor via an appropriate interface for signal conditioning. The programming of the training scenario, in particular the determination of the position of the nerve tracts, is done via the HMI device.

The anatomy model allows a direct representation of the intraoperative situation with a high level of detail. It consists of a plastic skull anatomy based on real computed tomography (CT) scan data. The surgical area manipulated by the surgeon (e.g. by milling) is designed as an interchangeable module, see Fig. 1. With these modules various special anatomies can be simulated. The anatomy model is available from Phacon GmbH. It is mechanically modified to include the sensor system.

2.2 Magnetic tracking

The magnetic tracking method is an extension of the method described in [5]. It uses several Hall effect sensor modules, see Fig. 3, which are integrated in the anatomy model. Each module consists of three sensors which are arranged orthogonal. Nine of those modules are aligned in a grid of 3 $\times$ 3 which results in an area of about 20 $\times$ 20 mm. This area can be monitored up to a height of about 11 mm.

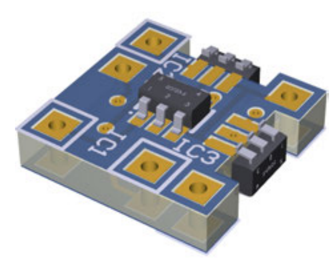

Fig. 3: Single Hall effect sensor module

A summary of the most important parameters of the Si7210 Hall sensor used, is presented in Tab. 1.

Tab. 1: Paramter Hall sensor Si7210

Parameter	Value	Unit
Range	$\pm$ 20	mT
Resolution	13	bit
Bandwidth	20	kHz
RMS noise	30	µT
Package	SOT 23-5	

The sensor has an integrated 13-bit AD converter. This results in a digital processing chain that makes filtering and compensation of the earth's magnetic field easy. The tip of the original stimulation probe of the neuromonitor is extended by a small magnet whose field is measured by the Hall effect sensors. This is a cylindrical neodymium magnet with a diameter of 4 mm and a length of 6 mm.

For calculating the position coordinates of the magnet, it is approximated as a magnetic dipole. This results in a regression problem consisting of n dipole equations

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \cdot \frac{3\vec{r}(\vec{m}\cdot\vec{r}) - mr^2}{r^5} \tag{1}$$

for n Hall sensors, 27 in the presented system. The magnetic dipole moment $\vec{m}$ produces a magnetic field density $\vec{B}$ at a distance $\vec{r}$. The magnetic field constant is described by μ_0 with the value of $4\pi \cdot 10^{-7}$ H/m. The regression problem is solved with a least mean squares algorithm based on the Levenberg-Marquardt method [6, 7]. The algorithm is programmed specifically for the microcontroller-based processing unit.

The tracking system is able to determine the position of the tool center point (TCP) of the stimulation probe with an accuracy of 0.2 mm. The precision of the system is determined by the measurement error of the Hall effect sensor which has a root mean square (RMS) noise of 30 µT. To determine the accuracy, the system is compared to a coordinate measurement solution of Faro inc., the FaroArm Fusion. The technical datasheet of the arm states the precision with $\pm$0.051 mm. Four measures are done in the corners of a plane of 20 $\times$ 20 mm which is located 11 mm above the sensor matrix top surface. These points were chosen with respect to the lowest signal to noise ratio of the Hall effect sensors output and thus the lowest accuracy of the TCP position calculation. To reduce the influence of the noise from the hall effect sensor is repeated the measurements 10 times per point. The highest Pythagorean distance error between the systems position measuring and the reference measure determine the accuracy.

A stored spatial model of the risk structure (nerve) is used to decide whether the stimulation occurs or not, i.e. whether an artificial EMG signal is emitted or not. The nerves surface is approximated with a linear interpolated grid and can be teached by the trainer. Therefore different anatomic models can be matched.

2.3 Signal Synthesis

For the EMG signal, the action potential [8] of a nerve has been synthesized in three stages, see Fig. 4. The output to the neuromonitor depends on the distance between the tip of the stimulation probe and the stored nerve position. The thresholds which triggers the signal stages can be adjusted by the trainer depending on the surgical scenario.

To increase the degree of reality the EMG signal is corrupted by an additive white noise with an amplitude of 3 mV. The EMG signals for drilling and coagulating were synthesized from recorded audio signals of the neuromonitor during a real surgery.

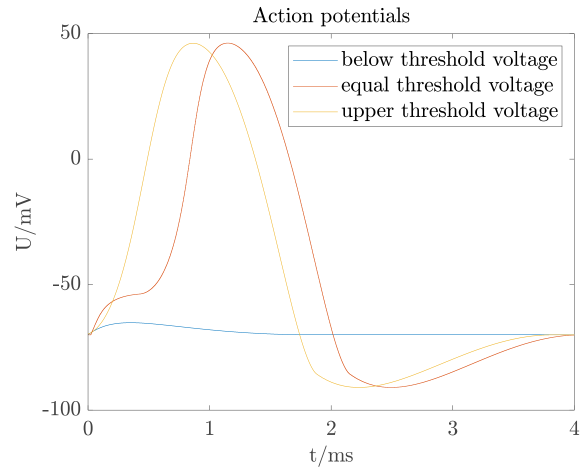

Fig. 4: Synthetic EMG action potentials

2.4 Training scenarios

The three presented training scenarios should be guided by an trainer which is experienced in the use of a neuromonitor in a surgical environment. The first scenario teaches the trainee how to use the neuromonitor. Therefore the starting point is a simple surgical phantom, as presented in Fig. 5.

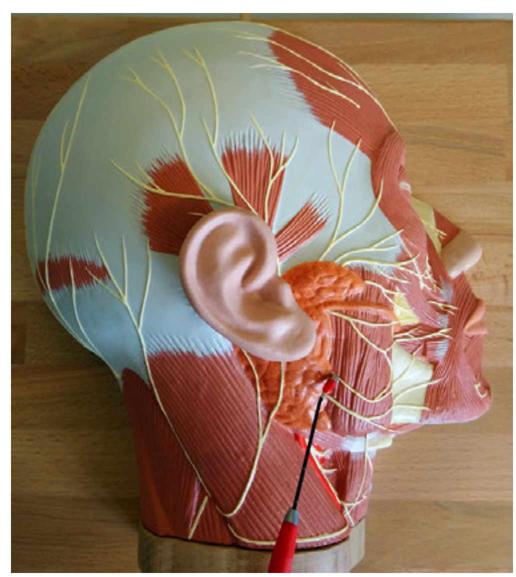

Fig. 5: Surgical model with nerves at the surface

Because the nerves are on the surface the trainee can understand easily what parameter of the EMG signal changes depending on the location of the stimulation.

The second scenario makes use of the surgical phantom as seen in Fig. 1. Here the focus lies on the use of the stimulation probe during a petrosal bone surgery. The trainee learns to locate the nervus facialis during different stages of the procedure. In every stage more abnormal mutated mastoid process is removed [9], see Fig. 6.

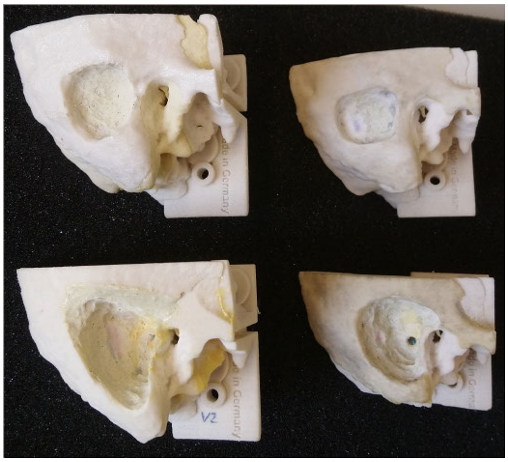

Fig. 6: Petrosal bone model in 4 stages of bone removal

The final scenario reproduces a complete mastoidectomy. So milling the mastoid is the beginning of the practical part of the training scenario. With increasing depth of the milling the trainee is starting to practice the localization of the nervus facialis with the neuromonitor.

The trainer can adjust the output of the neuromonitor in any scenario. The following parameters can be changed
– the delay of the EMG signal,
– the amplitude of the EMG signal,
– disruption of the EMG signal output and
– triggering the output of disturbance signals.

After the surgery the trainer gives the trainee feedback about success or failure.

3 Results and Discussion

The tracking system is able to determine the position of the tip of the stimulation probe with an accuracy of 0.2 mm in a distance of 11 mm from the sensor array. It can be shown that the tremor of the hand-guided stimulation probe is greater as the reached accuracy and therefore sufficient for the tracking of such. Therefore the EMG action potential can be generated in such a way that the trigger threshold of different signal stages can be adapted to the operative training situation. The resulting EMG signal and thus the output of the neuromonitor comes very close to reality. In addition, various complications during an surgery can be simulated, such as a faulty connection, wire break, defect in the device. The trainee learns to interpret the output of the neuromonitor in different operative situations. The trainer can choose different training scenarios, such as localization of the nerve, milling or coagulating, using a web application.

4 Conclusion

The presented simulation system is a tool for a realistic training for the use of intraoperative neuromonitoring in mastoidectomy. It allows the presentation of different operative scenarios, various situations and additional complications. This allows the surgeon to gain valuable experience, which reduces the risk of an application error. Due to the robustness of the magnetic tracking technique the system could also be adapted to scenarios which uses liquids in the situs. Furthermore, the simulation system can be used as a demonstrator to explain the functionality of intraoperative neuromonitoring.

Author Statement

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