2014 International Joint Conference on Neural Networks (IJCNN)
July 6-11, 2014, Beijing, China

# The Stapedius Reflex: Processing its Neuronal Activity with a Small Embedded System

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***Abstract*—Cochlear implants require a first calibration, which is usually done during surgery. This calibration is normally based on the inspection of the stapedius reflex, which is the contraction of a very tiny muscle in the inner ear. Even though being state-of-the-art, this visual inspection is limited and error prone due to various reasons. This paper proposes a small embedded system that automatically processes the action potentials of the stapedius muscle. Among other things, this process also signals the appearance of the stapedius reflex. Since particular emphasis is to keep computational demands as low as possible, the developed system may be integrated into future version of the implant's speech processor.**

## I. Introduction

Most readers have probably experienced that loudness can cause severe pain in a person's head. It is well known [1] that too much exposure to very loud sound sources can cause irreversible damage to the aural sense. Therefore, personnel, for example, is urged to wear proper ear protection during work, if working with heavy machineries, such as jackhammers and buzzsaws. The performance of the auditory sense very much depends on the ear. Fig. 1 shows the functional parts of the ear that mainly consists of the eardrum, the three auditory ossicles, malleus, incus, and stapes, as well as the cochlea. Among other things, the cochlea hosts approximately three thousands of inner hair cells. These hair cells transform the acoustic sound waves, which are mechanical by their very nature, into electrical signals, which are projected onto the auditory cortex by the auditory nerve.

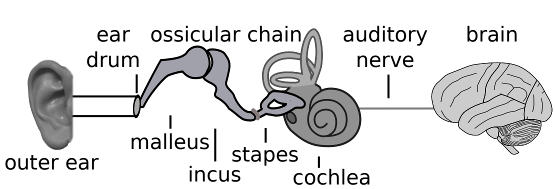


Fig. 1. Depiction of the human auditory system.

The cochlea's hair cells are very delicate structures, which can be easily destroyed by too much sound pressure, at least in the long-term. For their protection, nature has developed certain reflexes, that are triggered if the sound level exceeds a certain, personal threshold. At the behavioral level, subjects turn away or protect their ears with their hands and fingers. At the neuronal level, the auditory cortex initiates the contraction of the stapedius muscle, a very tiny skeletal muscle that connects the stapes with the skull.

Some believe that the main purpose of the stapedius reflex is to dampen the incoming sound signals, whereas others [2] do not fully agree with this interpretation. Regardless of the particular opinion on this question, it is commonly agreed that the appearance of the stapedius reflex is closely correlated with a loudness exceeding a personal threshold, which is also perceived as pain. In other words, the appearance of the stapedius reflex is associated with discomfort and is thus a rather undesired experience.

Besides the attributed protection, the stapedius reflex also plays an important role in the context of cochlear implants [3], [4]. A cochlear implant consists of two main parts, a speech processor and a set of up to 22 electrodes. The speech processor performs a frequency analysis of the external sound and electrically stimulates the corresponding hair cells by activating the proper electrodes. This way, a cochlear implant helps regain the auditory sense in cases where major portion or even *all* hair cells are destroyed.

In order to function properly, a cochlear implant has to be calibrated, which is typically initiated during implantation, i.e., during surgery; the calibration process continues during the next three to six weeks. From a technical point of view, calibration means the determination of the individual gains $g_i$ with which the electrodes are stimulated; since the electrical characteristic between an electrode and a hair cell usually changes over time and varies from electrode to electrode, the gains $g_i$ have to be *individually* adjusted as well. Such a calibration process has to know how a particular cochlear stimulation is perceived in the brain. For obvious reasons, however, the patient is not able to report the perceived loudness under anesthesia. Fortunately, the appearance of the stapedius reflex provides some valuable feedback as it indicates that the level of comfort is exceeded, as was already discussed above. It is state-of-the-art, to visually inspect the stapedius muscle during the implantation and to adjust the gains $g_i$ afterwards manually. For the interested reader, Appendix A provides further details on cochlear implants and the currently applied calibration procedure.

Even though being state-of-the-art, the visual inspection of the stapedius muscle is limited and error-prone to some extent. Some reasons are: the stapedius muscle is merely a few millimeters in size, it hides itself in a hollow, the pyramidal eminence, and the entire area is tainted by blood and other substances. Therefore, current research [5]–[7] aims to improving the calibration procedure by electrically observing and evaluating the neuronal activity of the stapedius muscle. For this purpose, previous research has developed new electrodes that are able to derive the stapedius muscle's action potentials. Section II discusses how this data can be processed in order to estimate the original cause, which is the perceived loudness in the problem at hand.

One long-term goal of the present research is to integrate the electrical detection of the stapedius reflex into a cochlear implant's speech processor, which provides only very limited computational resources.

Section III takes this shortcoming into account and proposes a suitable hardware-software concept. Particular emphasis is on computational requirements as low as possible. The result is an embedded system that uses 1032 summations, four multiplications, a shift operation, and an if-statement to estimate a muscle's activity.

Before being used productively, the developed system has to be evaluated. This, however, is not possible in a direct manner for the following reasons: sufficiently labeled stapedius data is not available; the developed forces of the stapedius cannot be measured, since it is attached to bones on both sides (no patient would agree on removing the muscle from the bone). Besides, every surgery involves the risk of infection. Therefore, Section IV proposes to evaluate the developed system at a large peripheral skeletal muscle, such as the soleus muscle and the quadriceps muscle. However, literature states different observations regarding the relationship of electromyographic signals (EMG) and exerted force [8], [9]. Anyhow, it is common knowledge that a higher EMG activity results in a higher force output [10]. The rational behind this introduced workaround is that the stapedius muscle is a skeletal muscle as well, and thus *structurally* identical with the aforementioned ones, which are more accessible, e.g., with surface mounted electrodes

Nevertheless, Section V processes the few available stapedius data samples. It turns out that the stapedius muscle behaves very similarly to the large skeletal muscles. A growing electrical stimulation inside the cochlea most likely causes a growing muscle activity. A mapping between the electrical stimulation and the resulting force shows a behavior that contains the four regimes 'idle' activity, sub-threshold, above-threshold and saturation. These results demonstrate the feasibility of the chosen approach. Finally, Section VI concludes this paper with a brief discussion and an outline of future research.

## II. Problem Description: Reverse Engineering of Muscular Activity

The introduction has outlined that the *perceived* loudness of a sound source is *the* required quantity for the initial calibration of a cochlear implant. However, narcotized subjects are not able to report this quantity. Furthermore, subjects who have been born deaf have no "hearing" experience and have thus no personal "loudness scale". The introduction has furthermore outlined that the stapedius reflex provides at least some indirect indication in that it appears, if the perceived loudness comes close to or exceeds the level of uncomfortableness. Therefore, the automatic detection of the stapedius reflex is the long-term goal of the present research.

Unfortunately, the nerve nervus facialis, which connects the brain with the stapedius muscle, is not a single "wire" that is activated in an information technology sense. Rather, the efferent signals have to pass various (neuronal) structures, such as the motor neurons. As a consequence, the stapedius muscle is not reached by a crisp signal but rather a set of many stochastic, uncorrelated spike trains. Furthermore, significant noise is added due to several reasons, e.g., the overlapping action potentials inside the muscle, and the crosstalk caused by the cochlear implant's stimulation. The resulting electrical signal, as derived by some electrodes from the stapedius muscle, is noisy by its very nature, as can be seen in Fig. 2.

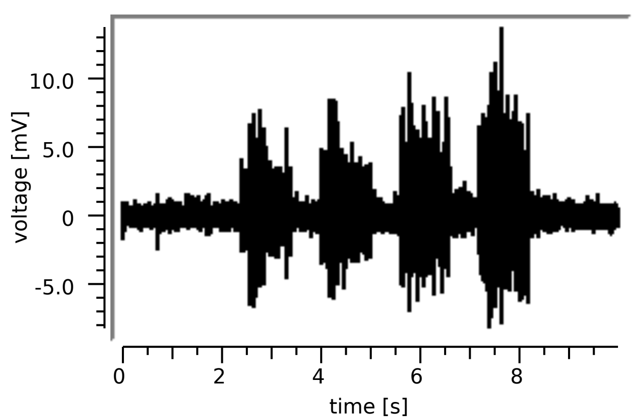


Fig. 2. Due to many physiological reasons, the electrical signal as derived from the stapedius is rather noisy by its very nature. Even though the signal corresponds to four different stimulations, the differences can be hardly detected by visual inspection.

In order to be technically useful, this derived data stream has to be amplified and processed in several stages as is illustrated in Fig. 3. The amplification is required, since the signal voltage provided by the electrodes is typically only a few millivolts. The subsequent processing chain practically calculates the envelope of the raw EMG data. The chain contains a bandpass, a rectifier, and an additional low-pass filter. The bandpass removes a large portion of the described crosstalk, the rectifier commutates the signal, and finally the low-pass filter smooths the signal. The low pass filter can be implemented as a digital filter but also as a moving average with a suitable window size. The resulting signal corresponds *qualitatively* to the cause, i.e., the exerted force of the stapedius muscle.

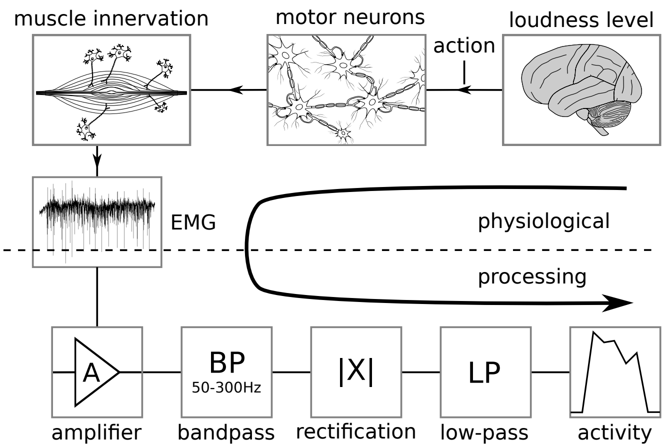


Fig. 3. From the nerval activity to the perceived loudness and back to the calculated activity. The upper part depicts the physiological domain, while the lower shows the EMG signal processing.

## III. The Embedded-System Approach

For the design of an appropriate test-and-development platform, the following constraints should be kept in mind:

1) The detection has to be performed *online* as an extension of the cochlear implant.
2) The seamless integration of an automatic stapedius reflex detector into existing cochlea implants is one of the major long-term goals of the present research project.
3) Since cochlear implants typically employ only very simple (speech) processors with a very small memory and a low clock frequency, the computational demands should be as small as possible.

Due to these constraints, this research project has designed a small embedded system, for which the block diagram is presented in Fig. 4.

The hardware system consists of (1) an analog subsystem that derives and amplifies the EMG signal and (2) the digital part that calculates the envelope curve. For the analog part a special electrode [11] is used that derives the signals at the tiny stapedius muscle. The linked amplifier (EMG-amplifier, biovision) uses a gain of 3000 such that the analog-to-digital converter can sample the EMG signal. The sampling rate is set to 5000 samples per second. The analog-to-digital converter is a part of a general purpose microcontroller (ATxmega128B1, ATMEL), which calculates the envelope curve in the digital domain. The used 4th-order Butterworth bandpass filters the digitized signal with cut-off frequencies of 50 and 300 Hz. To reduce the complexity and computational demands, an averager is employed that has a window size of 1024 samples (205 ms) and replaces the low

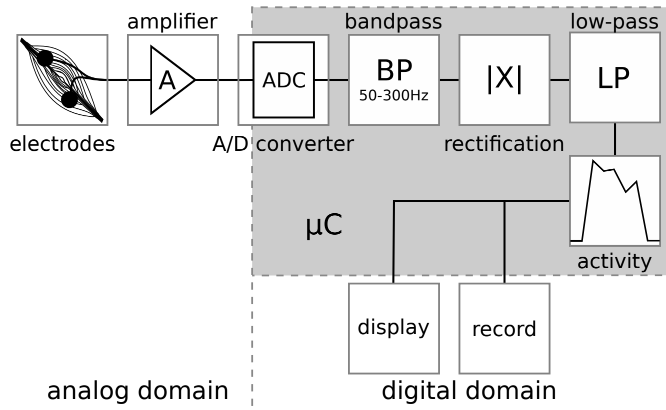


Fig. 4. Embedded System of a Stapedius Reflex Detector.

pass filter. The system shows the activity on a display and stores the values for potential ongoing analysis and future research. The entire system configuration allows for short development cycles, realistic in situ testing, as well as an easy monitoring and evaluation. The studies were approved by the local ethics committee.

## IV. System Evaluation

The introduction has already outlined that several physical constrains turn the system evaluation into a significant challenge. Due to the lack of sufficient labeled stapedius data, the present research has adopted a work around presented in Fig. 5. Therefore, the quadriceps femoris muscle and the soleus muscle of an male subject were observed to get labeled data.

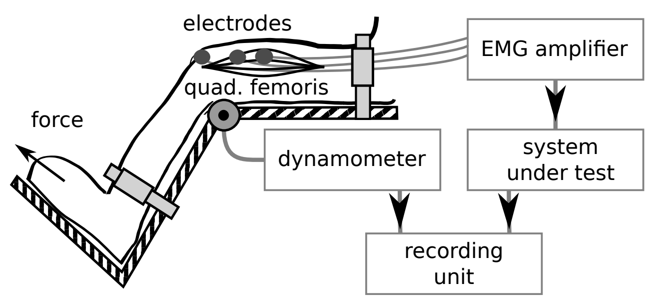


Fig. 5. Measurement setup for the quadriceps femoris muscle. The electrodes measure the EMG signal, while the dynamometer records the exerted torque.

The introduced muscle activity detector measures the EMG activity of the thigh muscle. The dynamometer measures the torque in the knee joint. Data is derived by surface-mounted electrodes and recorded by a recording unit. A similar setup was used to measure the torque in the ankle and the corresponding EMG emitted by the soleus muscle. The connected recording unit stored all resulting data sets. Figure 6 shows the outcome of the quadriceps femoris measurement. The resulting envelope estimates the exerted torque of the muscle. The same applies to the data set measured at the soleus muscle. Figure 7 shows the resulting curve. All the graphs show that the system *qualitatively* reconstructs the exerted force as desired.

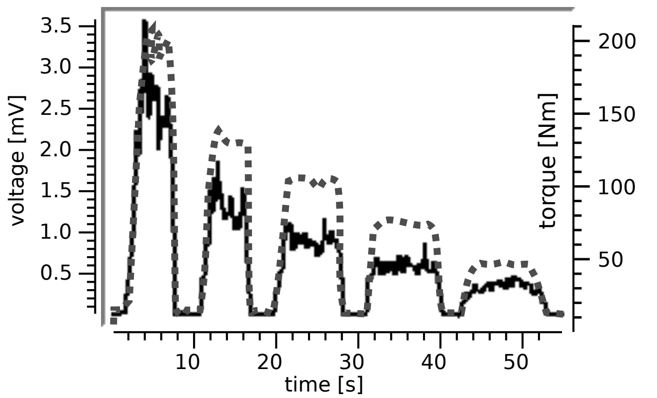


Fig. 6. Quadriceps femoris muscle (solid = EMG activity; dashed = torque)

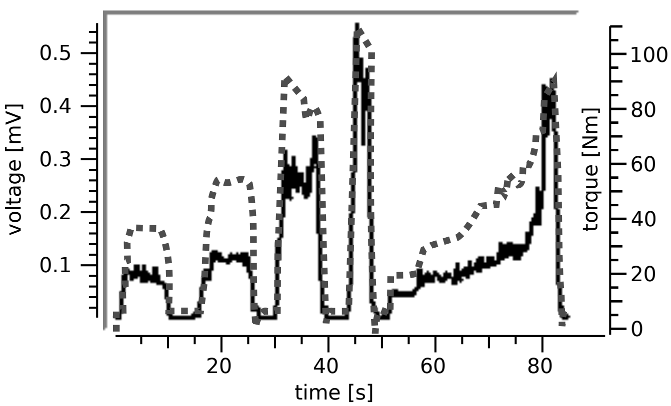


Fig. 7. Soleus muscle (solid = EMG activity; dashed = torque)

## V. Results on the Stapedius Muscle

The muscle activity detector system showed a similar activity for the stapedius muscle during surgery. The stapedius reflex was provoked (1) acoustically with an ear-plug in the contralateral ear (opposite side) and (2) on the ipsilateral side (side under surgery) with a cochlear implant. Both patients were anesthetized with propofol.

For both measurements, the graphs show a significant change in stapedial activity. As can be seen in Fig. 8, the acoustically evoked stapedial activity started slightly above 100 dB(SPL). An averaging over the stimulus' period, shows a nearly linear increase of activity along with an increase of the stimulation intensity. The electrically evoked stapedial activity, in turn, shows a different characteristic as can be seen in Fig. 9. The stimulation level above 25 nC caused a nearly constant activity. This area certainly shows the saturation of the stapedial system. On the other hand, stimulation below 18 nC presumably evoked only 'idle' activity as it did not change with a decreasing stimulation level. In between these stages the activity changes significantly. In fact, the surgeon documented the visible reflex threshold at 23.4 nC. Hence, only the above-threshold stage seems to be visible but the actual stapedial activity and thus the nerval activity starts at a lower stimulation level. Both experiments point to a continuous characteristic curve of the stapedial activity, which allows for the online adaptation of cochlear implants by means of such a stapedius reflex detector.

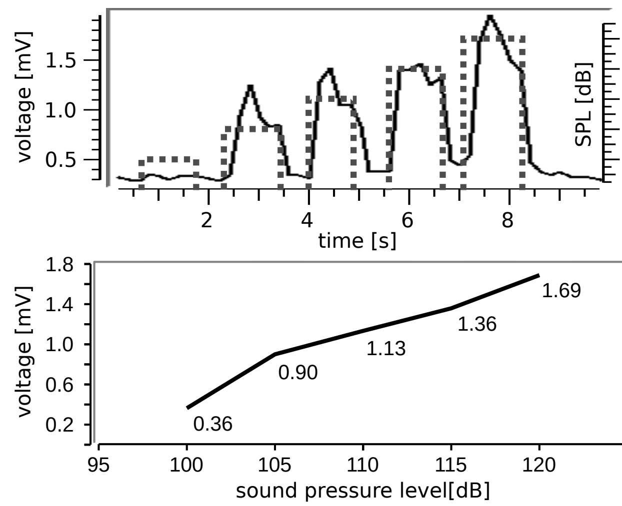


Fig. 8. The upper graph shows the acoustically evoked stapedius responses (solid = EMG activity; dashed = acoustical stimulation as sound pressure level). The lower graph plots the average of the activity for each stimulation over the stimulations amplitude.

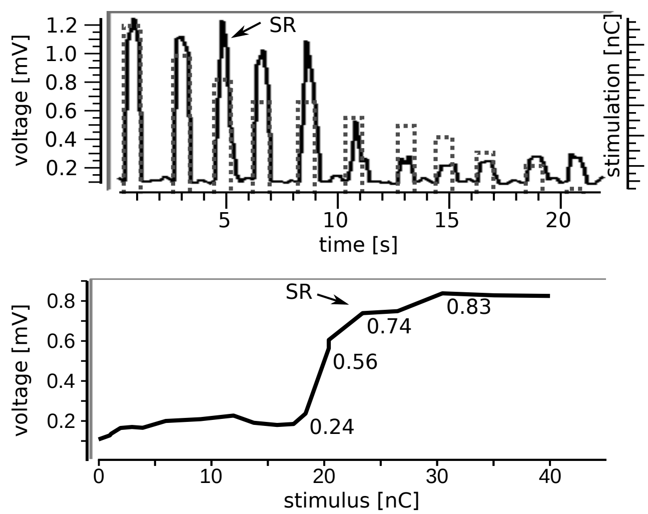


Fig. 9. The upper graph shows the electrically evoked stapedius responses (solid = EMG activity; dashed = electrical stimulation as introduced charges). The lower graph plots the average of the activity for each stimulation over the stimulations amplitude. The arrow marks the visible stapedius reflex threshold(SR).

## VI. Discussion

This paper has discussed the importance of the stapedius reflex in the context of cochlear implants and particularly its initial calibration. It has furthermore been explained that the current procedure of visually inspecting the stapedius muscle is state-of-the-art but quite error prone due to several reasons.

In order to overcome these problems, this paper has proposed a small embedded system that monitors, processes, and interprets the action potential it derives from the stapedius muscle. As a result, this system "reconstructs" the force the stapedius muscle develops as a result of its neuronal stimulation. It has then been discussed that due to the lack of access of appropriately labeled stapedius data, the system has to be evaluated at some other, easily accessible large skeletal muscles, such as the soleus muscle and the quadriceps muscle. And indeed, the stapedius muscle exhibits the same qualitatively behavior as those large muscles.

The amount of currently available test data is rather small. Therefore, future research will be to collect and process new data in cooperation with the otolaryngologist Prof. Pau at the University of Rostock. This data will be collected from patients who are subject to an implantation of a cochlear implant as well as from animals.

A second avenue of future research will be using the developed system as a basis of a new self-adaptation mechanisms for cochlear implants. In essence, this system will be monitoring both the neuronal activity of the stapedius muscle and the external loudness. Depending on the deviation with respect to a pre-specified mapping, the system will be adapting the individual gains $g_i$ of the implant's electrodes.

Finally, the third part of future research will further reduce the computational requirements of the developed system; the expected results will be making it easier to integrate the system into the implant's speech processor.

## ACKNOWLEDGEMENT

The authors gratefully thank Ralf Joost and Matthias Hinkfoth for their very fruitful comments on draft versions of this paper. Special thanks are due to Martin Behrens for helping with the force-measurement experiments. This work was supported in part by the DFG graduate school 1505, 'welisa'.

## APPENDIX A

**Medical Indication:** The cochlea is an organ that is part of the inner ear. Roughly speaking, it is a spiral-shaped tube (see, also, left-hand-side of Fig. 10) that hosts among many other things, about 3500 inner hair cells. Every hair cell consists of a cell body and some stereocilia (tiny 'hairs') (see, also, right-hand-side of Fig. 10). All hair cells convert mechanical energy, conveyed by some inner-tube fluids, into electrical signals, which are projected onto the auditory cortex via the ear nerve. In essence, these hair cells, due to the support of some further mechanical mechanisms, perform a frequency analysis, with the amplitude being coded into the hair cell's electrical excitation.

It might happen that due to too much external noise, birth defects, or other reasons, the hair cells get damaged. In particular, it might be that in many cases, the damage occurs as broken-off hairs such that the energy conversion cannot be performed anymore. In these cases, a cochlea implant can employ artificial electrodes that take over the electrical stimulation of the hair cells' bodies.

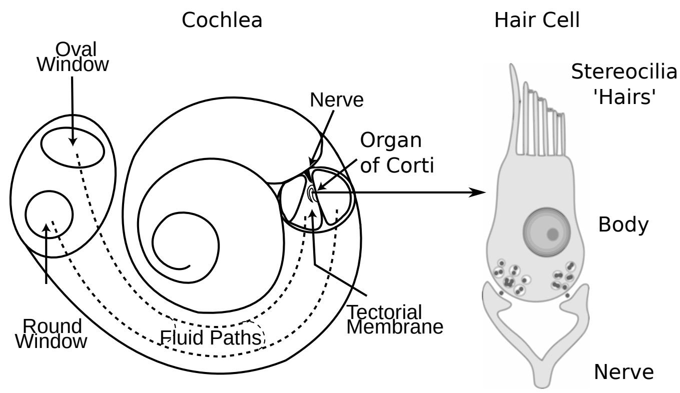


Fig. 10. The left-hand-side of the figure [12] shows a spiral-shaped cochlea, whereas the right-hand-side shows a hair cell [13], which consists of its body and stereocilia.

The description presented above is very simplified and has only the intent to help understand the content of this paper. The more interested reader is referred to the pertinent literature of some publicly accessible web pages [14].

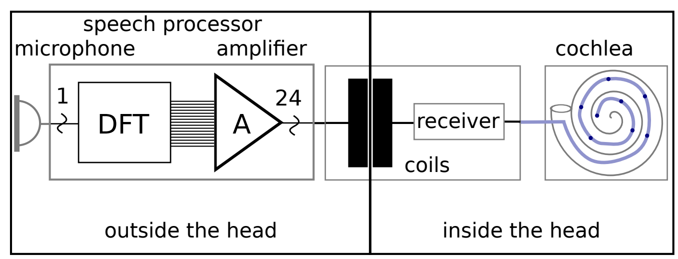


Fig. 11. The figure shows that a cochlea implant mainly consists of a microphone, a speech processor, two electromagnetic coils, a receiver, and the electrodes that stimulate the corresponding hair cells.

**Cochlea Implants:** Figure 11 shows that a cochlea implant mainly consists of the following parts: a microphone, a speech processor, two electromagnetic coils, a receiver, and the electrodes. The microphone receives the external sound signals, which are analysed by the speech processor, which in turn activates the electrodes via the two coils and the receiver. In essence, the speech processor performs a frequency analysis (DFT) on the fly, and activates every electrode and thus the nearby hair cell according to the corresponding spectral energy density; this concept holds at least to a large extent.

**Implantation and Initial Calibration:** The critical point of the implantation is that the electrodes have to be inserted into the cochlea. To this end, a surgery takes place. In order to achieve an acceptable perception of the external sound sources, the entire cochlear implant has to be calibrated. To this end, the surgeon has to determine the amount of the per-electrode stimulation that exceeds the level of comfort, which corresponds to the appearance of the stapedius reflex. To this end, the surgeon activates every electrode at varying strengths, and *visually* observes the stapedius muscle. For obvious reasons, this procedure can be applied only during anesthesia, which makes it a on-time only method. Furthermore, this process of visual inspection of the stapedius muscle is very error prone for the following reasons: the muscle is only a few millimeters in length and the tissue area around the stapedius muscle contains significant amounts of blood and other body fluids.

After surgery, the patient has to visit a specialist in regular turns for a recalibration of the implant. This recalibration is necessary, since the area and thus the electrical parameters may change around every single electrode. Therefore, an automatic recalibration would be beneficial at least for the patients.

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