Hear Restore RTD 2013

Development of a Mathematical Model of the Electrical Properties of Bone

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Scope and Purpose

Direct Cochlear Access (DCA) aims to replace mastoidectomy

- Cochlear implants are successful hearing aids.
- Surgical procedure is complex and invasive.
- Replace invasive mastoidectomy by minimal invasive drilling [1].
- No visual access to OP field
- Narrow drilling trajectory sets important nerves at risk
- Electromyography (EMG) has been proposed to assess drill to nerve distance [2].
- Current development lacks sensitivity and specificity.
- Bone electric properties required to improve safety.

Materials & Methods

Determination of the electrical properties of bone tissue [3].

- Evaluation and development of tools to measure bone properties in-vivo.
- Development of Electrical Impedance Spectroscopy signal protocol.
- Determine and minimize adverse influences on measurement system.
- Impedance measurement of the sheep mastoid bone.
- Development of measurement setup to in-vivo measure bone impedance in a sheep model
- Apply electro impedance spectroscopy (EIS) sinusoidal waveforms with frequencies 15Hz, 110Hz and 1070Hz and current magnitudes of 125µA, 250µA and 500µA.

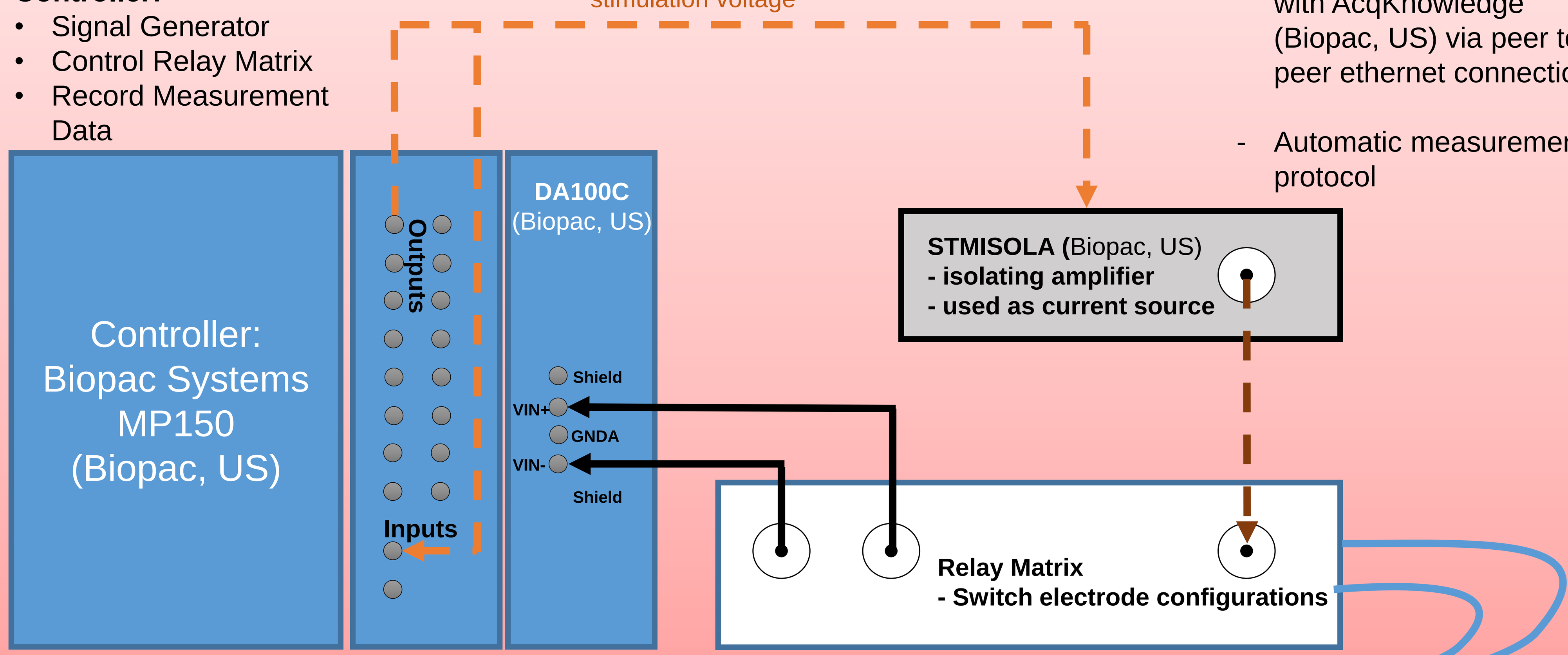
⇒ Quantify the conductivity of the mastoid bone.
⇒ Determine direct relationship between the electric impedanceand density and distance.

Measurement setup

Controller:

- Signal Generator
- Control Relay Matrix
- Record Measurement Data

- Control Biopac System with AcqKnowledge (Biopac, US) via peer to peer ethernet connection.
- Automatic measurement protocol



Surgical procedure

1. Robot drills into sheep mastoid (Fig1) till end position.
2. Remove DCA drill bit.
3. Replace drill by multi electrode probe (Fig2 & Fig4).
4. Insert second multi electrode probe in predefined drill hole.
5. Measure impedance.

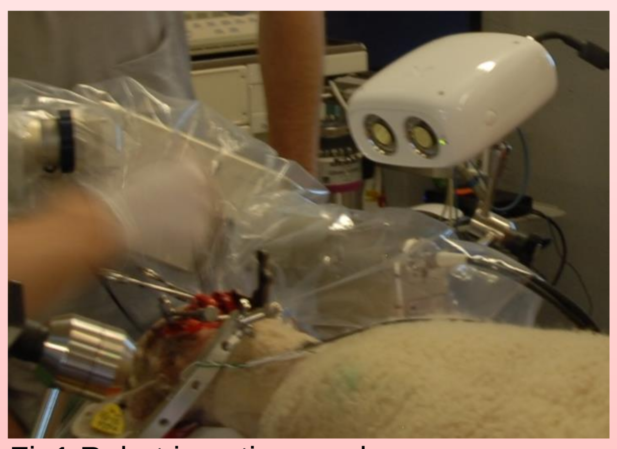


Fig1:Robot in action on sheep

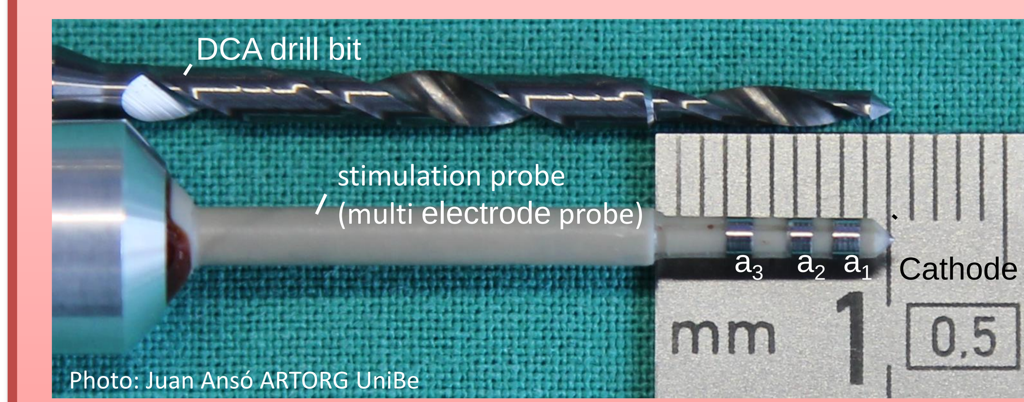
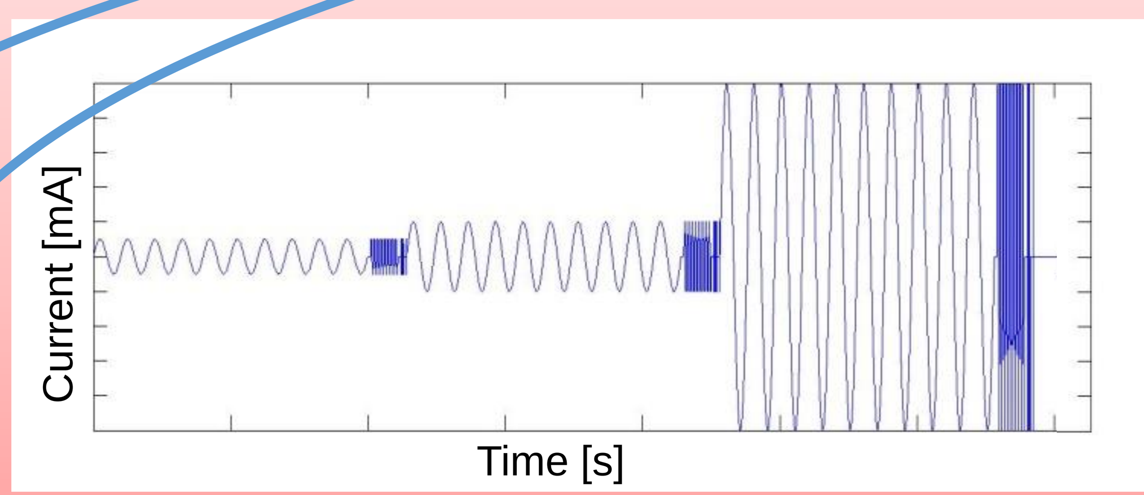


Figure 2: DCA drill bit & stimulation probe have the exact same outlines.

Stimulation current signal

Amplitudes: 125µA, 250µA, 500µA
Current is chosen below 500µA to not overstimulate the sheep's facial nerve.

Frequencies: 15Hz, 110Hz, 1070Hz
128 sine periods per frequency leads to a duration of approximately one minute signal time.



Equivalent Circuit: Constant Phase Element CPE

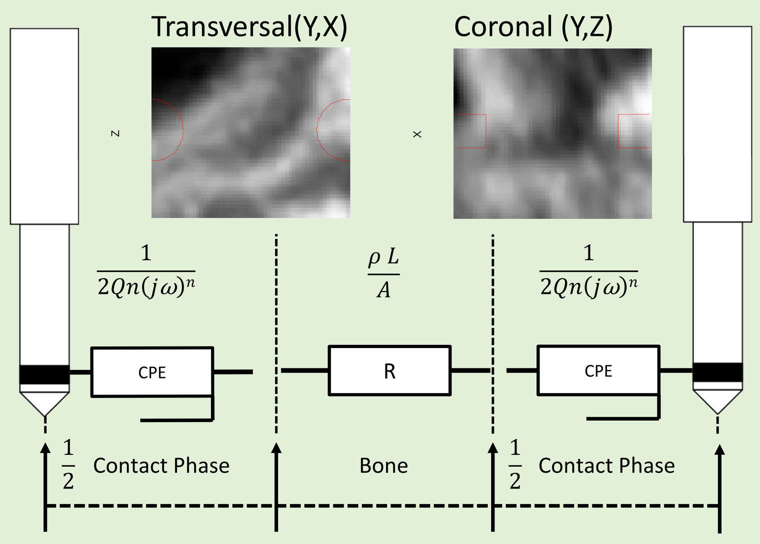


Figure 5: The equivalent circuit used to model bone impedance was composed of a constant phase element (CPE) in series with resistor R. The CPE is symmetrically aligned at the contact phase where the steel electrode touches the bone tissue. This model allows to separate the real resistance of the bone from the hardly controllable phase shift introduced by the contact phase.

The multi electrode probes are manually inserted. Then the automatic protocol is started.

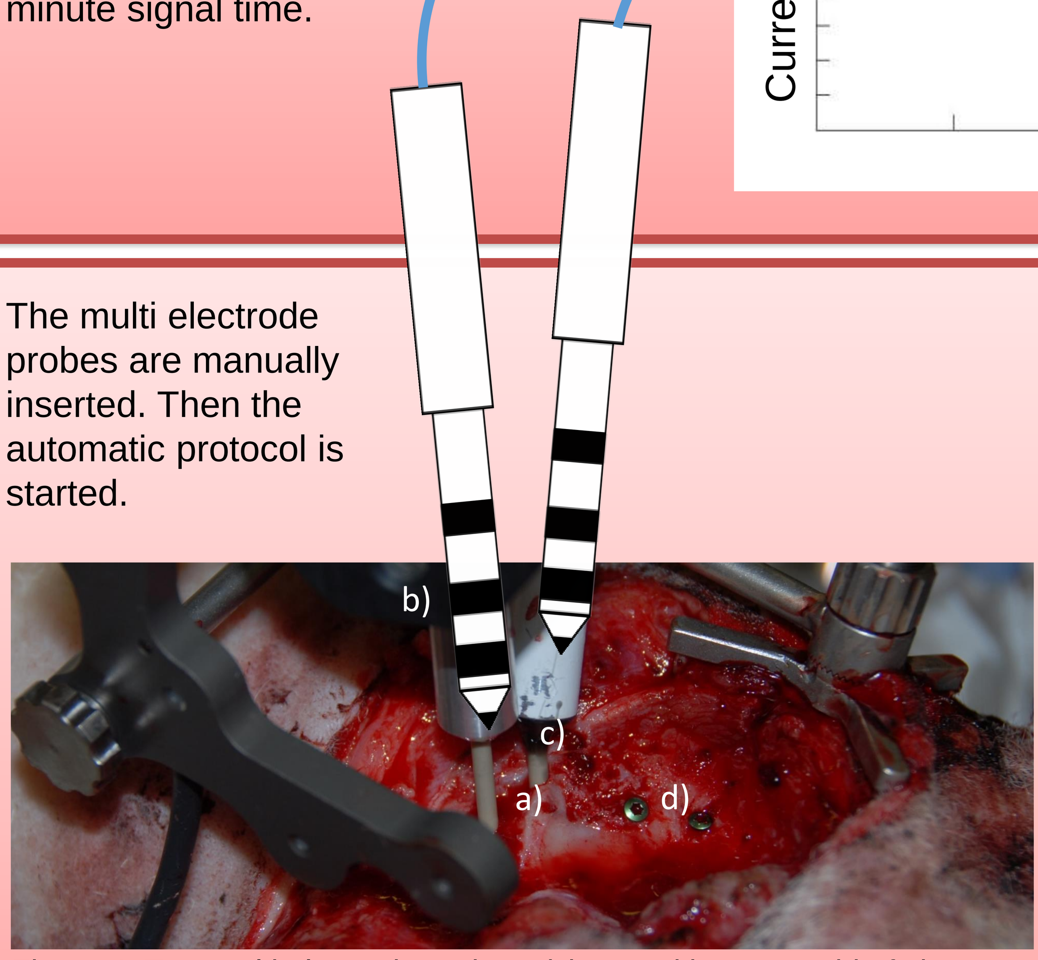
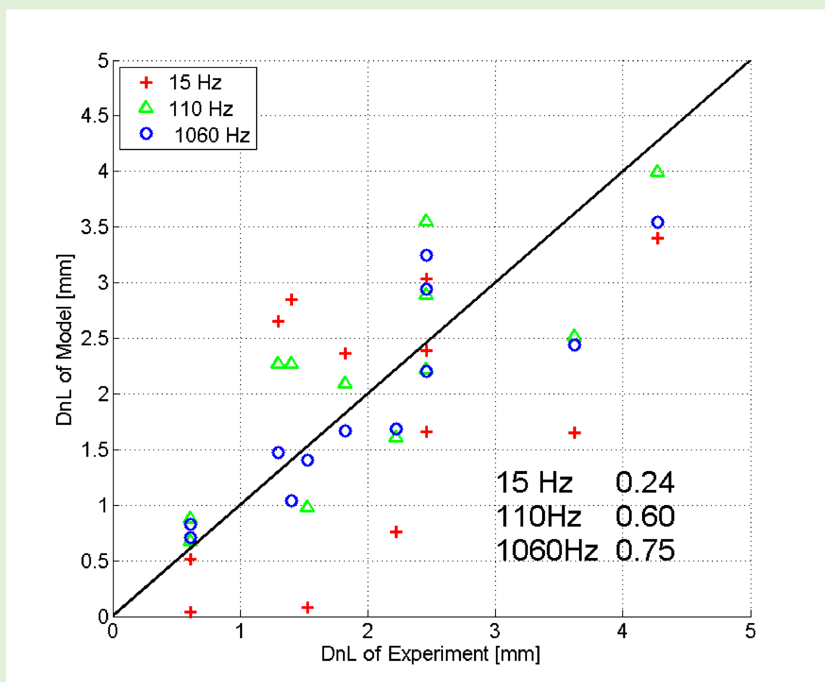


Figure 4: Two multi electrode probes a) inserted into mastoid of sheep model. The position of the main probe was recorded by the 3D navigation system of the robot b). a counter probe c) was applied to measure impedance. Fiducial screws to determine position of the mastoid d).

Results

Figure 6: The scatterplot relates the product of bone density and inter-electrode distance (D_N*L) calculated from the model resistance R with D_N*L of the tunnel where the current flows between the electrodes... Analysis of the resistance calculated with the simplified circuit showed a strong correlation of this resistance with, D_N*L whereby the correlation (r^2=0.75) is best for the experimental data at 1060 Hz.(Table2).



Parameter	STD [%]	confidence interval
ρ = 14.3±2.1Ωm	14.4 %	10.1 Ωm – 18.5Ωm
Q_0 = 2.70 10^{-5} ± 0.8 10^{-5}	29.3 %	1.1 10^{-5} – 4.3 10^{-5}
n = 0.47 ± 0.06	13.5%	0.34 – 0.60

Tab1: Properties of equivalent circuit (Figure 5) determined by nonlinear least mean square fitting.

Frequency	15 Hz	110 Hz	1060 Hz	All
Error Magnitudes Difference	15.7 %	20.8 %	24.6 %	20.4 %
Exp Data AVG re/im	4.04 kΩ/2.96 kΩ	2.40 kΩ/1.11 kΩ	1.70 kΩ/542 Ω	
STD / % of Exp AVG Real	622 Ω / 15.7 %	75 Ω / 3.21 %	16 Ω / 0.80 %	6.58 %
STD / % of Exp AVG Imag	1.08k Ω / 36.1 %	150 Ω / 12.2 %	40 Ω / 7.83 %	18.7 %
STD / % of Exp AVG	1.25k Ω / 24.9 %	174 Ω / 6.50 %	45.1 Ω / 2.54 %	11.3 %
Correlation DnL model to DnL experiment	0.24	0.60	0.75	

Tab2: Error to the model, average values and standard deviation of the experimental data. The relative error of the model impedance to the measured impedance overall is about 20 %...

Discussion

The **impedance** measured **in-vivo** could be described by a simple **electronic circuit composed of a resistor in series with a constant phase element**. Interestingly, the **same set of parameters** could be used to describe the behavior of the constant phase element for all the experimental measurements. This result indicate that the **phase shift** observed in the experimental impedance **could be explained by the impedance at the bone/electrode interface** caused by the **polarization of steel electrodes**. The interface between the electrodes and the body fluids is **similar for all the measurement configuration** and does not depend on the inter-electrode distance nor on the bone density. Therefore, our results support the hypothesis that the **constant phase element describes the constant polarization** and electrochemical processes happening at the bone/electrode interface. On the other hand, the **resistor component** of the circuit **differs for each measurement.** This resistance showed a high **dependence to the average bone quality and inter-electrode distance**, which corresponds to the representation of bone tissue as a perfect resistor. In addition, the model can be used to **predict the complex impedance** of the bone **based on pre-operative imaging** – to determine the average bone density – and the measurement distance.

[1] B. Bell, N. Gerber, T. Williamson, K. Gavaghan, W. Wimmer, M. Caversaccio, and S. Weber, "In vitro accuracy evaluation of image-guided robot system for direct cochlear access.," *Otol. Neurotol.*, vol. 34, no. 7, pp. 1284–90, Sep. 2013.

[2] J. Ansó, C. Stahl, N. Gerber, T. Williamson, K. Gavaghan, M. Caversaccio, S. Weber, and B. Bell, "Feasibility of Using EMG for Early Detection of the Facial Nerve During Robotic Direct Cochlear Access."

[3] J. Sierpowska, J. T yr s, M. A. Hakulinen, S. Saarakkala, J. S. Jurvelin, R. Lappalainen, and J. Töyräs, "Electrical and dielectric properties of bovine trabecular bone--relationships with mechanical properties and mineral density.," *Phys. Med. Biol.*, vol. 48, no. 6, pp. 775–86, Mar. 2003.