INTRODUCTION

Acoustic neuroma (AN) is a benign tumor that may develop on the hearing and balance nerves near the inner ear which, depending on its size, affects hearing of the affected subjects. The incidence has been estimated to be between 7 and 15 people per million, and constitutes about 80% of all tumors found in the cerebellopontine angle [1-3]. Patients diagnosed with an AN can potentially be faced with 3 management options: observation, the active treatments of microsurgery, or radiation. Especially for patients diagnosed with an AN, acoustic neuroma, acoustic neuroma etc. If due to tumor growth or radiation therapy hearing is affected beyond the possibility of conventional hearing aid treatment and reconstruction surgery (including partial- and total middle-ear prostheses), implantable hearing devices may be applicable. Besides cochlear implants, which are indicated for patients with profound hearing loss or deafness, bone-conduction hearing implants (BCI) and active middle-ear implants (aMEI) may effectively rehabilitate mild-to-moderate or mild-to-severe hearing losses. Based on the here presented patient’s hearing loss, bone conduction devices are further exploited. All available BCI- systems are characterized by excellent sound-transmission properties of the skull bone. Sound is picked up by the externally worn audio-processor.
microphones (AP) and converted into vibratory stimuli which are either applied directly to the bone ('direct-drive' percutaneous: Baha, Ponto, or 'direct-drive' transcutaneous: Bonebridge) or indirectly via the skin ('skin-drive' transcutaneous: Sophono and Baha Attract) [5]. Both device categories contain magnetic and electrically conductive materials inducing difficulties when undergoing MRI measurements or even hindering diagnosis if artefacts occur within the area of interest. An artefact sphere of 15 cm in diameter was reported with Bonebridge (BCI601) [6], a distance of 5–10 cm from the Sophono implant [7], and 11.5 cm from the center of the Baha Attract implant [8]. Most hearing implant manufacturers nowadays make their products MRI – conditional [9-11], and allow temporal explanations of the magnet for diagnostic purposes [12]. However, this implies two surgical procedures for the patient: one to explant and one to re-implant the magnet during which time the implant cannot be used, resulting in ‘no hearing’ for the patient. Besides the effects of the MRI and the potential explanation for easier access, the main disadvantages of percutaneous systems, such as the Baha are related to its abutment, and include skin reaction, wound infection, growth of skin over the abutment, and implant extrusion with major complications in up to 37% of the infant cases [13]. However, even with a simplified surgical technique using a linear incision, extrusion rates have been reported in 9.3% of the cases [13]. Motivation for these experiments was a female case of acoustic neuroma presenting to the clinic after with mild to moderate mixed and conductive hearing loss. The hearing loss resulted from an incomplete tumor resection due to the intra-operative association of the tumor with a potential facial nerve injury by the neurosurgeon. The patient has shown a stable disease without tumor growth for two years, but she considerably suffers from the negative impact on quality of life and shows mild signs of depression following the untreated hearing loss. After two years of unsuccessful conventional hearing aid trials, she insisted on an implantable solution. The possible rehabilitation options for her given indication (transcutaneous versus percutaneous systems) were discussed with the hospital implant board which recommended, for both audiological and wearing-comfort reasons, the direct-drive options were then presented to the patient. Following thorough explanations and counseling regarding the possible artefact which may hinder her diagnostic AN management, the patient decided to get the active transcutaneous Bone Conduction Implant (Bonebridge, BCI602, MED-EL, Innsbruck, Austria). Despite being MRI conditional up to 1.5 Tesla (T), as stated above, the reported artefact size of the precursor model, the BCI601, is approx. 15 cm around the implant side and may also be present on the images on the contralateral side of the head [14,15]. Utrilla et al., also reported substantially reduced artefact size (almost 50% compared to the previous generation) with the new generation BCI602, especially when Metal Artefact Reduction Sequences (MARS) were applied [14], from now on referred to as reduction sequences or MARS. The imaging artefacts do not only depend on the type of implant and the scanning parameters but also on the position of the implant in relation to the site of interest. Therefore, not only MRI safety for hearing implants is essential but also the possibility to reduce the implant shadow and artefact region to allow for comprehensive clarification of diagnosis.

The aim of this study was to evaluate the possible correlation of customized metal artefact reduction sequences with three different anatomical implant positions on artefact size in a cadaver head implanted with the newest generation of active transcutaneous bone conduction implant.

**MATERIAL & METHODS**

**System description and MRI conditionality**

The latest generation of active Bone Conduction Implants, the BCI602 (MED-EL, Innsbruck, Austria), was used; it addresses the most reported disadvantage of its precursor model the BCI60 – the size of the implanted Bone Conduction-Floating Mass Transducer (BC-FMT). The new generation presents with almost half the size of the previous generation, allowing implantation with a drilling depth of 4.5mm (equal to the drilling depth of a Baha-screw) which makes pre-surgical planning redundant and allowing for more individual positioning options, as investigated in this study. The BCI602 device used was provided by the manufacturer (MED-EL, Innsbruck, Austria). The BCI 602 is MRI conditional at 1.5T without the need to surgically remove the magnet. The MRI scanner was limited to “normal operating mode” (whole body averaged specific absorption rate (SAR) of <2 W/kg), “first level controlled operating mode” was avoided.

**Specimen preparation**

One fresh frozen cadaver head was obtained from the Institute of Anatomy, Medical University of Vienna, Austria. The fresh frozen condition enabled surgical preparation under conditions close to the intravital situation. Three different anatomical positions were prepared as indicated in Figure 1: superior to the middle fossa, the classical sinodural angle, and the classical middle fossa position; and emphasis was placed on beneficial coil position for beneficial and normal post-operative AP application.

**MRI measurements**

The cadaver head was supine positioned without the need of additional fixation in the MR scanner according to the standard position in routine clinical practice.

All scans were obtained in a commercially available 1.5 T MRI scanner applying different specifications (SIEMENS® 1.5 T ALLEGRA MRI scanner) (Table 2). DICOM data from the MRI series of the patients were retrieved from PACS (picture archiving system) and transferred to a computer, which contains the SYNERA AIM 15 “Odysseus” software (version 15.0.0.3 x64 Edition). The SYNERA software is available as a freeware from Synedra Information Technologies GmbH (Innsbruck, Austria). This software contains tools for measuring and defining distances and volume values. Using this software, artefacts around each implant were compared to the full head image radius measurement in different series (axial T1, axial T2, coronal T1 and coronal T2) (Figure 2).

**Imaging evaluation**

The artefact surrounding the implant was evaluated both qualitatively and quantitatively. For quantitative purposes, we calculated the percent ratio of full head area to the area of the artefact (B) in all measured sections (Figure 2). The diagnostic
Table 1:

<table>
<thead>
<tr>
<th></th>
<th>T1 Area (mm²)</th>
<th></th>
<th>T2 Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No MARS</td>
<td>SEMAC-VAT WARP</td>
<td>No MARS</td>
</tr>
<tr>
<td>Pos 1</td>
<td>35.26</td>
<td>14.32</td>
<td>17.50</td>
</tr>
<tr>
<td>Pos 2</td>
<td>19.05</td>
<td>81.53</td>
<td>34.00</td>
</tr>
<tr>
<td>Pos 3</td>
<td>22.25</td>
<td>50.34</td>
<td>24.00</td>
</tr>
<tr>
<td>Min.</td>
<td>35.26</td>
<td>14.32</td>
<td>17.50</td>
</tr>
<tr>
<td>Max.</td>
<td>62.57</td>
<td>40.23</td>
<td>27.50</td>
</tr>
<tr>
<td>Median</td>
<td>44.72</td>
<td>27.67</td>
<td>24.61</td>
</tr>
<tr>
<td>Mean</td>
<td>46.72</td>
<td>26.84</td>
<td>24.00</td>
</tr>
<tr>
<td>SD</td>
<td>8.379</td>
<td>18.29</td>
<td>16.38</td>
</tr>
</tbody>
</table>

P value

Min, Max, Median, Mean±SD and P-value outcomes for T1- and T2-weighted area for the three tested implant positions (1 superior to middle fossa, 2 sinodural angle and 3 classical middle fossa) and with and without metal artefact reduction sequences (SEMAC-VAT WARP).

Table 2:

<table>
<thead>
<tr>
<th>Scan parameters</th>
<th>Axial T1 without artefact reduction</th>
<th>Axial T1 SEMAC WARP VAT</th>
<th>Axial T2 without MARS</th>
<th>Axial T2 with MARS</th>
<th>Coronal T1 with MARS</th>
<th>Coronal T2 with MARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR 490, TE 8.7</td>
<td>flip angle 150</td>
<td>slice thickness 5mm</td>
<td>matrix 320x280</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 256x204</td>
</tr>
<tr>
<td>TR 650, TE 7</td>
<td>flip angle 130</td>
<td>slice thickness 3mm</td>
<td>matrix 256x179</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 320x256</td>
</tr>
<tr>
<td>TR 3500, TE 102</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 256x204</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 320x256</td>
</tr>
<tr>
<td>TR 5300 TE 85</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 320x256</td>
<td>flip angle 150</td>
<td>slice thickness 3mm</td>
<td>matrix 320x256</td>
</tr>
</tbody>
</table>

Scanning parameters for the T1 or T2 weighted measurements applied on every anatomical position.

Figure 1 shows the experimental positioning of the BCI602. Position 1: superior to middle fossa; Position 2: classical sinodural angle; Position 3: classical middle fossa. (Left) cadaver head with the BC-FMT implant bed drilled. (Right) schematic presentation of the BC-FMT and coil position, hence planned AP placement.

usefulness and qualitative image analysis of the acquired MRI scans were rated by a consultant radiologist (Figure 4). Focus was put on the visualization of the brain, the cerebellopontine angle (CPA), and internal auditory canal (IAC) adjacent to the artefact. The ability to visualize the internal auditory meatus (IAM) and cerebellopontine angle (CPA) cistern for the sides ipsilateral and contralateral to the BCI602 was assessed for the measurement series axial T1, axial T2, coronal T1, and coronal T2 for all three anatomical implant positions.

RESULTS

The study compared possible MRI artefact reduction possibilities by investigating different implant positions as well as applying metal artefact reduction sequences. The image acquisition time was 12 min and 20 s for the T1-weighted and

Figure 2 T1-weighted axial MRI scans with the respective measurement taken for width (C) and area of the implant (B) and for the full head (A). (Left) image without reduction sequences, (right) with SEMAC-WARP-Vat Sequences applied.
Figure 3 Box-plot showing the T1-weighted relative area of artefact to head in percent (%) for the three placement positions. Pos1: superior to middle fossa; Pos2: classical sinodural angle; Pos3: classical middle fossa. Ends of the box are the upper and lower quartiles, so the box spans the interquartile range. The median is marked by a vertical line inside the box.

Figure 4 Visualization of the brain adjacent to the artefact of the BCI602 with a zoom-in of the area of interest: the cerebellopontine angle, and internal auditory canal fully visible.

12 min and 12 s for the T2-weighted MRI. Globally, the artefact related to the BCI602 was less prominent in the axial plane than in the coronal plane. Furthermore, only the axial plane allowed for the visualization of the brain parenchyma, the CPA, and the IAC, and therefore the focus of the evaluation was directed towards the axial plane measurements. The ratio of full head to artefact size compared to no reduction sequences was investigated for T1- and T2-weighted scans in the axial plane.

The customized SEMAC-VAT WARP sequences significantly decreased the relative artefact area (%) in the T1 and T2-weighted outcomes for the measured positions (Figure 3 and 4). In the T1-weighted area, the experimental superior to middle fossa position artefact size reduced by 42.5% compared to the no reduction sequences applied (P=0.0004; Table 1), and sinodural angle, the artefact reduction difference was 25.02% for the classical middle fossa and 24.02% for the sinodural angle compared to no reduction (P=0.0249, P=0.0214; Table 1). No significant difference was found between the three positions applying SEMAC-VAT-WARP reduction sequences. Investigating the diameter of the artefact in T1-weighted area, the SEMAC-VAT-WARP reduction sequence reduced the mean artefact width in Position 1 from 7.53±1.02 cm (range: 5.90 - 9.07 cm) to 6.80±1.30 cm (range: 4.71 - 9.02 cm), which translates into a 9.71% reduction in size. Position 2 revealed a mean artefact width of 7.14±1.86 cm (range: 5.05 - 11.66 cm; reduction of 5.13%), and Position 3 a mean artefact width of 6.92±1.65 cm (range: 4.67 - 9.81 cm; reduction of 8.05%) (Figure 1).

In the T2-weighted measurement the relative artefact area (%) in the superior to middle fossa position with SEMAC-VAT-WARP was significantly reduced compared to no reduction sequences (P<0.0001) as well as compared to the two classical approaches of middle fossa (P<0.0001) and sinodural angle (P=0.009). The two classical approaches significantly differed from each other (P=0.0136) but were not significantly different when compared to the no reduction sequences applied. Investigating the diameter of the artefact in T2-weighted area, the SEMAC-VAT-WARP reduction sequence reduced the mean artefact width in the superior to middle fossa position from 7.53±1.02 cm (range: 5.90 - 9.07 cm) to 6.80±1.30 cm (range: 5.42 - 9.97 cm), which translates to a reduction of 18.65% in artefact width. The classical sinodural angle position exhibited a mean artefact width of 7.20±1.76 cm (range: 3.89 – 10.48 cm), and in the classical middle fossa position a mean artefact width of 8.45±1.06 cm (range: 6.51 – 9.91 cm) was found (Figure 1).

The qualitative analysis revealed that the superior to middle fossa position approach allowed for a better evaluation of the CPA and IAC, with similar accuracy in the evaluation of the brain parenchyma (Figure 5). When artefact reduction sequences were applied, less artefact and better evaluation for both the brain parenchyma and cerebellopontine angle, and internal auditory canal evaluation were possible.

DISCUSSION

The aim of this study was to evaluate the possible correlation of customized metal artefact reduction sequences with different anatomical implant positions on artefact size in a cadaver head implanted with the newest generation of active transcutaneous bone conduction implants.

The major aim was the visualize the internal auditory meatus and cerebellopontine angle cistern for the sides ipsilateral and contralateral to the BCI602, for the purpose of regular diagnostics in an acoustic neuroma case without the need for implant or implant magnet removal. Motivation for these experiments was a female case of acoustic neuroma requiring regular MRI diagnostics of the respective position. This study suggests that patients diagnosed with acoustic neuroma and an active hearing implant can still undergo regular MRI examinations for routine diagnostic clarification of tumor growth. Despite the possibilities to undergo MRI for routine clarification in this special case, complications associated with the magnet of implantable...
hearing devices are reported. For counselling purposes of the subject, an internal literature screening on MRI with all hearing implants was performed and resulted in 34 studies with a total of 440 patients out of which 215 underwent 368 scans in total [11,16-30]. Of the 215 patients with MRIs done, 82 were from MED–EL, 70 from Cochlear Limited, 22 from Advanced Bionics, 4 from Oticon, 6 from the Technical University of Vienna, 11 from Soundtec and 1 from Xomed. None of the extracted studies reported, pain, discomfort or abortion of the scans with the Bonebridge BCI601 device (MED-EL), the precursor model of the here investigated implant. No cadaver studies on the sole focus of the clinical application of MRI with the BCI602 generation have been published yet [14]. This is also one of the limitations of the present study: clinical issues such as demagnetization, discomfort, pain, or even movement of the implant during MRI testing could not be measured. The study by Utrilla et al., investigated both implant generations in cadaver specimens and found similar improvements in artefact reduction when applying another type of artefact reduction sequences, the so called MAVRIC. The authors also concluded that for their research the middle fossa approach allowed for a better visualization of respective brain structures with both implant versions, but the effect was more prominent with the BCi602 [14]. Also worth mentioning is the fact that different surgical approaches have been described for Bonebridge implantation. The most widely used is the sinodural or mastoid position. 15 followed by retrosigmoid [13], and middle fossa approach [15,31]. The rather experimental superior to the middle fossa position of the BC-FMT was performed with emphasis on a beneficial coil-position and almost similar to the classical AP position. The rounded and smoothened form and the substantially reduced size of the BC-FMT in the new generation BCI 602 is neither expected to have a negative effect on the patients hearing impression nor alters the known wearing comfort despite its relatively superior position on the skull. However, we have no experience on this matter, and we were not able to find research or publications on this subject. Importantly though, no audiological differences in those implant positions were found but similar low rates of complications and surgical times were reported [15]. The superior to the classical middle fossa position had not been used and/or published up to the conduct of the present study to the best knowledge of the authors. Especially for this placement, to ensure comfortable, aesthetical and beneficial AP placement, emphasis was placed on an as low as possible coil position for the AP, and only the BC-FMT was placed higher than usual.

The calculated ratio of full head to artefact size in percent compared to no reduction sequences revealed that applying the customized SEMAC-VAT WARP sequences significantly decreases the relative artefact area in the T1-weighted measurements for all three measured positions (experimental superior to middle fossa, the classical middle fossa, and sinodural angle) compared to no reduction sequences, but especially prominent in the experimental position superior to middle fossa. Similar but less significant results were seen in the T2-weighted measurement where the relative artefact area in the superior to middle fossa position with SEMAC-VAT-WARP was significantly reduced compared to no reduction sequences (P<0.0001) and compared to the two classical approaches of middle fossa (P<0.0001) and sinodural angle (P=0.009). The two classical approaches significantly differed from each other (P=0.0136) but were not significantly different when compared to the no reduction sequences applied. The results suggest that the experimental position superior to the middle fossa seems to be the most favorable placement to ensure diagnostic imaging quality, particularly on the implanted side.

**CONCLUSION**

The experimental superior to middle fossa placement allowed for better visualization of the brain areas (especially when affected by acoustic neuroma) when compared to the classical sinodural and classical middle fossa approaches. Imaging of intracranial and supra- and infratentorial brain pathologies are clinically more valuable than standard diagnostic
MRI without any artefact reduction sequences. The sequence for metal artefact reduction enables 1.5T MRI in patients with the Bonebridge BCi602 without sacrificing diagnostic imaging quality, particularly on the implanted side.

**Bullet Point Summary:**

- Acoustic Neuroma incidence estimation: 7 - 15 people per million, and about 80% of those tumors are found in the cerebellopontine angle
- MRI is gold-standard for tumor detection, but implant artefacts (BCi602) may hinder regular diagnosis of possible tumor growth
- Correlation of three implant positions (superior to middle fossa, classical middle fossa and sinodural angle positions) and MRI customized metal artefact suppression sequences were investigated
- The superior to middle fossa implant position of the Bonebridge BCi602 allows for detailed visualization of the cerebellopontine angle, hence regular screening of the tumor area

**Ethical Standards**

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional guidelines on human cadaver experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

**REFERENCES**

8. MED-EL The BONEBRIDGE™ Bone Conduction Implant System.