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Preservation of Basal Inner Ear Structures in Cochlear Implantation

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Cochlear Implant · Cochleostomy · Inner ear trauma · Electric-acoustic stimulation

Abstract
The aim of this report was to examine basal trauma in implanted human temporal bones and discuss modified approaches to the basal cochlear turn to avoid destruction of basal cochlear structures. Thirty-three human temporal bones were implanted with four different cochlear implant electrode arrays manufactured by MED-EL using either a caudal approach cochleostomy or round window membrane insertions. All specimens were processed with a special histological technique that allows sectioning of undecalcified bone with the electrode in situ. All bones were evaluated histologically in terms of basal cochlear trauma. Two pathomechanisms of basal trauma could be distinguished and were evaluated separately, buckling of the basal end of the array and trauma by drilling. Using the caudal approach cochleostomy, the total percentage of destructive basal trauma was 48% compared to less than 15% when performing round window membrane insertions. Although it is still unclear whether basal cochlear trauma influences apical cochlear function or not, adapted surgical procedures and no forceful insertion maneuvers should be used when performing cochlear implantations with hearing preservation.

Introduction

Cochlear implants stimulate the auditory nerve via direct activation of neuronal structures in the temporal bone. The presence of these structures is fundamental to the functional outcome of the system. Clinically, screening procedures like preoperative MRI scans of the temporal bone and electroaudiometry were established to verify the existence of neural structures. However, trauma to cochlear structures caused by the insertion of a cochlear implant array into the cochlea may lead to unwanted degeneration of neurons through the activation of enzymatic cascades and the release of neurotoxic factors [1] and fibrosis inside the cochlear ducts. Yet unpublished results from our own lab showed, that the topical application of corticosteroids with prolonged cytoprotective effect (triamcinolon) during cochlear implantation decreases postoperative impedances. This might contribute to the inhibition of fibrotic reactions and the preservation of neural structures.

With the development of the combined, ipsilateral electric-acoustic stimulation (EAS) [2, 3], where hearing preservation is fundamental, the issue of traumatizing delicate intracochlear structures became even more important [4]. Low frequency parts of the apical cochlea should retain residual function even after implantation to provide for bimodal stimulation. With the remaining cochlear function intact, high speech discrimination

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scores were possible in every subject, especially in noise conditions [5].

In a previous study undertaken in our laboratory, a modified electrode design for the combined EAS was evaluated (Flex^{EAS} array) [6]. Ideally, an electrode for EAS should not damage cochlear structures. In our temporal bone experiment, the array itself did not cause severe trauma except in the basal turn of the scala tympani, especially near the site of cochleostomy. Although intact regions of the organ of Corti within the ears with residual hearing are in most cases located apically, basal trauma might lead to functional impairment in the low frequency areas. As shown before, the mélange of endolymphatic and perilymphatic fluids leads to degeneration of hair cells and neuronal structures [7, 8]. The site of cell death, however, might not be limited to those basal regions of the organ of Corti. With the induction of a longitudinal cochlear flow by drilling the cochleostomy, apical structures may also be damaged. This was described as the double membrane leak syndrome [9].

Adequate surgical procedures should be capable of leaving basal structures of the cochlea intact. Therefore, the aim of this report was to examine the basal cochlear trauma in a greater series of implanted fresh human temporal bones and discuss modified approaches to the cochlea to avoid destruction of basal cochlear integrity.

Materials and Methods

Electrodes Used

Thirty-three fresh human temporal bones were removed up to 24 h postmortem and relayed for implantation with four different cochlear implant electrode arrays, manufactured by MED-EL, Innsbruck, Austria. We used the Flex^{EAS} (n = 11) from our previous series, the Flex^{soft} (n = 6), the regular C40+ (n = 13), and the C40+ M (n = 3) electrodes. The body of all electrodes is made of two-component medical grade silicon. All electrodes have platinum contacts, which are distributed over a length of either 26.4 mm (C40+ and Flex^{soft} arrays) or 20.4 mm (C40+ M and Flex^{EAS}). In case of the long arrays (C40+ and Flex^{soft}) the total length of the intracochlear part of the electrode (until the marker ring) is 31.5 mm, whereas the respective length in the shorter versions (C40+ M and Flex^{EAS}) is 25.1 mm. Whereas in the C40+ and C40+ M electrodes, all contacts are paired with two juxtaposed contact areas, in both Flex arrays the five apical contacts are unpaired to reduce the diameter at the tip by 30% and reduce stiffness of the distal electrode part. The basal diameter of all arrays is 0.80 × 0.78 mm. The apical diameter of the C40+ and C40+ M electrodes is 0.50 × 0.48 mm. The apical diameter of the Flex arrays is 0.50 × 0.35 mm.

Surgical Approach

All bones were implanted using a standard cochlear implant approach, including mastoidectomy and posterior tympanotomy via facial recess. In 25 specimens, a regular caudal approach (anteroinferior to the round window) cochleostomy was used (table 1), whereas in 8 bones, insertions were performed via the round window membrane (table 2). Here, the bony overhang covering the round window niche was removed to visualize the round window itself. The scala tympani was then opened by a lateral incision of the membrane to avoid interference with basal cochlear structures. All electrode insertions were then performed along the outer wall of the basal scala tympani to protect intracochlear structures.

All implantations were performed by two experienced cochlear implant surgeons (O.A. and J.K.) under standardized conditions. Healon® was used as a lubricant in all implantations. In all specimens, implantations were stopped at the point of first resistance to avoid further trauma. No forceful procedures were used for implantation. Electrodes were fixed onto the temporal bones using sutures.

Specimen Preparation

Then, all specimens were relayed for fixation and embedding. Fixation was accomplished via perilymphatic perfusion of buffered formalin solution followed by dehydration with an ascending alcohol series (70–100% ethanol). For embedding, polymethylmethacrylate at room temperature (20 °C) was utilized. A conventional x-ray analysis [10, 11] of the embedded specimens was performed afterwards to identify the location and orientation of the cochlea and inserted electrode within the temporal bone. Insertion depths in terms of degrees around the modiolus were measured. Serial sections with a slide thickness of 100 µm at a 90° angle between the sectioning plane and the electrode orientation at the site of the cochleostomy were made. Additionally, sections were grinded and polished. This special embedding and sectioning technique allows the processing of undecalcified bones with the electrodes in situ [12]. Visualization was enhanced with a regular Giemsa staining.

Evaluation of Insertion Properties

Intracochlear insertion depths were determined using the x-ray, the surgical report, and the histological data. Intracochlear position and extent of trauma were evaluated using a grading scheme established by Eshranghi et al. [13] (table 3). This allows for a standardized report of trauma data. Special emphasis was laid on basal cochlear trauma. To distinguish the pathomechanisms of basal trauma (direct destruction of basal structures via drilling or basal buckling of the electrode array into the basilar membrane), sections were analyzed according to the following scheme: if the drilling cone of the cochleostomy directly leads into the basilar membrane, a direct damage is suggested. If the drilling cone and the location of the basilar membrane are separated, basal bulging by the electrode carrier is suggested.

Results

By processing human temporal bones with the electrode in situ, insertion properties of each specimen were evaluated. Orientation and location of the cochlea within all the specimens was clearly visible during the x-ray examination performed prior to sectioning. Also, radiological insertion depths in terms of degrees around the modiolus were measured. Histologically evaluated inser-

Table 1. Implantation data, extent of basal cochlear trauma when using a caudal approach cochleostomy

Electrode and temporal bone			Insertion depths			Basal trauma	
#	side	type	surgical mm	histological degrees	radiological degrees	basal trauma*	cause of basal trauma**
1	left	C40+ Standard	20	270	270	2	cochleostomy
2	left	C40+ Standard	20	270	270	4	cochleostomy
3	left	C40+ Standard	24	270	180	0	no trauma
4	right	C40+ Standard	16	300	270	2	bulging
5	right	C40+ Standard	23	420	400	0	no trauma
6	left	C40+ Standard	19	300	270	0	no trauma
7	right	FLEXsoft	24	360	390	1	bulging
8	left	FLEXsoft	30	740	720	4	bulging
9	right	FLEXsoft	30	720	630	4	cochleostomy
10	right	FLEXsoft	20	420	360	0	no trauma
11	right	FLEXsoft	24	600	570	4	bulging
12	right	FLEXsoft	23	400	360	0	no trauma
13	right	Flex EAS	22	360	360	0	no trauma
14	right	Flex EAS	22	630	600	0	no trauma
15	right	Flex EAS	22	360	360	0	no trauma
16	left	Flex EAS	22	360	360	2	bulging
17	right	Flex EAS	22	360	420	4	cochleostomy
18	left	Flex EAS	22	360	360	0	no trauma
19	right	Flex EAS	22	270	240	0	no trauma
20	right	Flex EAS	20	360	360	4	bulging
21	left	Flex EAS	22	360	330	0	no trauma
22	right	Flex EAS	22	300	290	4	cochleostomy
23	right	C40+ M	17	270	300	4	cochleostomy
24	right	C40+ M	19	360	225	4	cochleostomy
25	right	C40+ M	19	270	330	0	no trauma
Min			16	270	180		
Max			30	740	720		
Mean			21.8	387.6	369.0		
SD			3.1	134.7	129.0		
	8 × left 17 × right	6 × C40+ Standard 6 × Flex Soft 10 × Flex EAS 3 × C40+ M				12 × grade 0 1 × grade 1 3 × grade 2 0 × grade 3 9 × grade 4	12 × no trauma 6 × bulging 7 × cochleostomy

* Grading according to Eshranghi et al, 2003 [13].

** Buckling means an indirect traumatizing of basal structures through a buckling of the electrode array, cochleostomy means a direct destruction of basal structures by the drilling of the cochleostomy.

tion depths correlated well with the radiological data. No statistically significant differences where seen when comparing histological and radiological insertion depths (Mann-Whitney U, $p > 0.05$).

The basal trauma was evaluated histologically. In all specimens implanted via the caudal approach cochleostomy, the emphasis of the processing process was to visualize the promontory cochleostomy and adjacent basal cochlear parts. Here, serial sections with a 90° angle between the electrode array in the basal cochlear turn and the sectioning plane were very effective. After a thorough investigation of all specimens, basal trauma was related to either the surgical procedure or the bulging of the basal electrode parts towards the basilar membrane.

Caudal Approach Cochleostomy

Histologically evaluated insertion depths for the C40+ electrode ranged from 270 to 420° with a mean value of

Table 2. Implantation data, extent of basal cochlear trauma when using a round window membrane approach

Electrode and temporal bone			Insertion depths			Basal trauma	
#	side	type	surgical mm	histological degrees	radiological degrees	basal trauma*	cause of basal trauma**
26	left	C40+ Standard	27	360	330	0	no
27	left	C40+ Standard	30	450	540	4***	cochlear anatomy
28	left	C40+ Standard	30	540	540	4	bulging
29	left	C40+ Standard	26	360	360	0	no
30	right	C40+ Standard	29	450	450	0	no
31	left	C40+ Standard	25	270	300	0	no
32	right	C40+ Standard	26	270	270	0	no
33	left	Flex EAS	19	360	360	0	no
Mean			26.5	382.5	393.75		
Min			19	270	270		
Max			30	540	540		
SD			3.4	87.1	97.7		
	6 × left	7 × C40+				6 × 0	6 × no
	2 × right	1 × Flex EAS				2 × 4	1 × bulging
							1 × cochlear anatomy

* Grading according to Eshranghi et al, 2003 [13].
** Buckling means an indirect traumatizing of basal structures through a buckling of the electrode array, cochleostomy means a direct destruction of basal structures by the drilling of the cochleostomy.
*** Grade 4 trauma throughout the entire extent of the inserted array due to an anatomically small cochlea.

305.0° (standard deviation – SD: 53.2°). Respectively, the C40+ M carrier had 270–360° (average 300.0°, SD 42.4°), the Flex^{soft} 360–740° (mean 540.0°, SD 154.1°), and the Flex^{EAS} electrode was inserted from 240 to 600° with a mean of 368.0° (SD 91.2°).

Overall, basal grade 4 trauma (fracture of the osseous spiral lamina) was seen in 9 specimens (36%) whereas grade 2 trauma (rupture of the basilar membrane) was present in 3 bones (12%). A slight lifting of the basilar membrane (grade 1) resulted in 1 bone, whereas a basal grade 3 trauma (dislocation into the scala vestibuli) was not found in any specimen. Excluding grade 1 trauma, which represents only a slight dislocation of the basilar membrane, the total percentage of destructive basal trauma (grade 2, 3, or 4); was 48% (12 of 25 bones). Distinguishing the pathomechanisms of basal trauma, 6 bones (24%) had basal trauma due to bulging of the basal end of the electrode carrier within the scala tympani and in 7 bones (28%), basal trauma is related to the drilling of the cochleostomy itself. Basal grade 4 trauma was seen in 3 of the Flex^{EAS} carriers (33.3%), 3 Flex^{soft} (50.0%), 1 C40+ (16.7%), and 2 of the C40+ M (66.7%) electrodes. Results and implantation data are shown in table 1.

Table 3. Grading of insertion trauma*

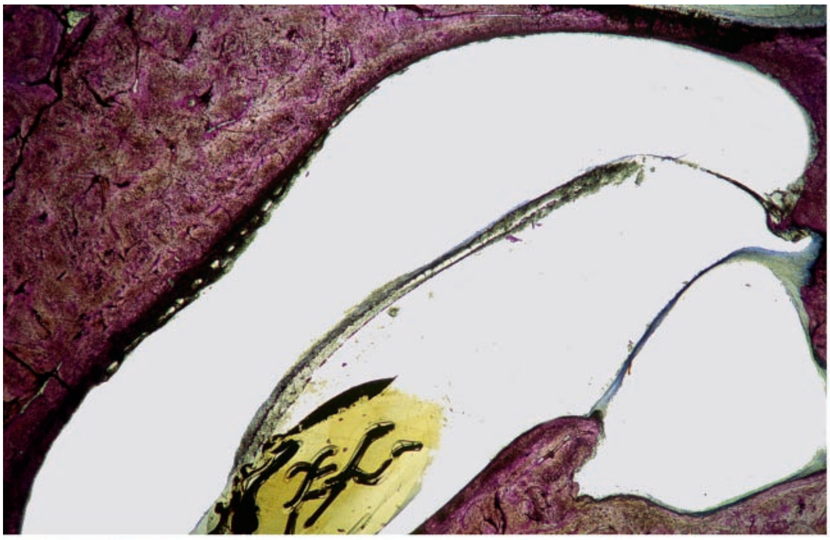
Grade	Histopathological changes
0	no trauma
1	elevation of basilar membrane
2	rupture of basilar membrane or spiral ligament
3	dislocation into scala vestibuli
4	fracture of osseous spiral lamina or modiolar wall

* Grading according to Eshranghi et al. 2003 [13].

Round Window Membrane Insertions

The average histological insertion depth for both the electrodes used was 382.5° (from 270 to 540°, SD 87.1°). Six left, and 2 right human temporal bones were used.

Basal grade 4 trauma was present in 2 specimens (25%). In one of those bones, fracture of the osseous spiral lamina occurred throughout the entire extent of the inserted array. Although no swelling of the electrode carrier was visible, the overall cochlear diameter in this specimen was only slightly larger than the electrode diameter itself. Due to this exceptionally small cochlear anatomy, 1



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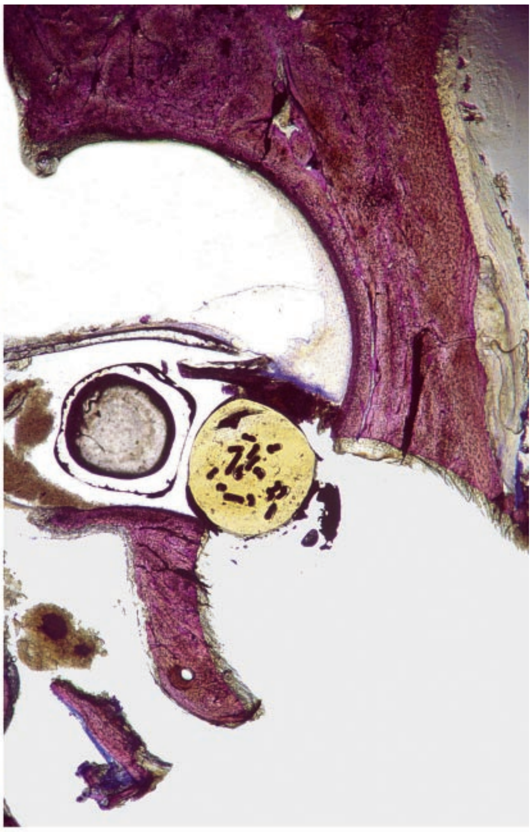

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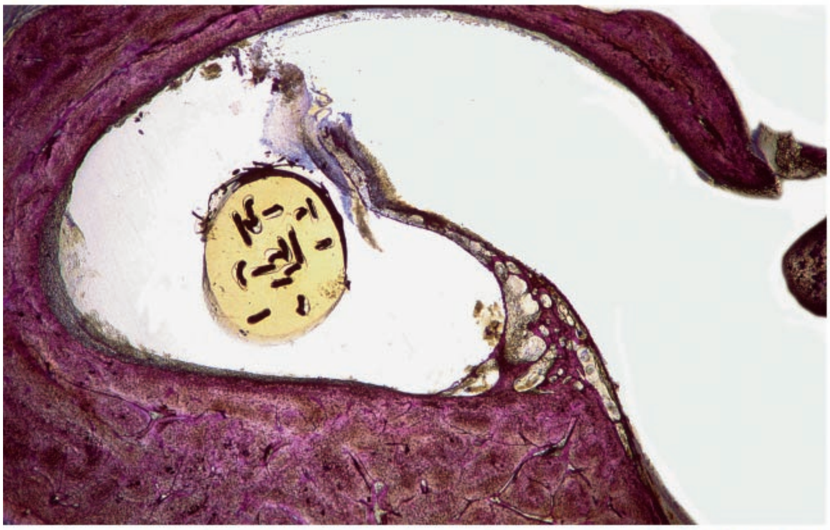

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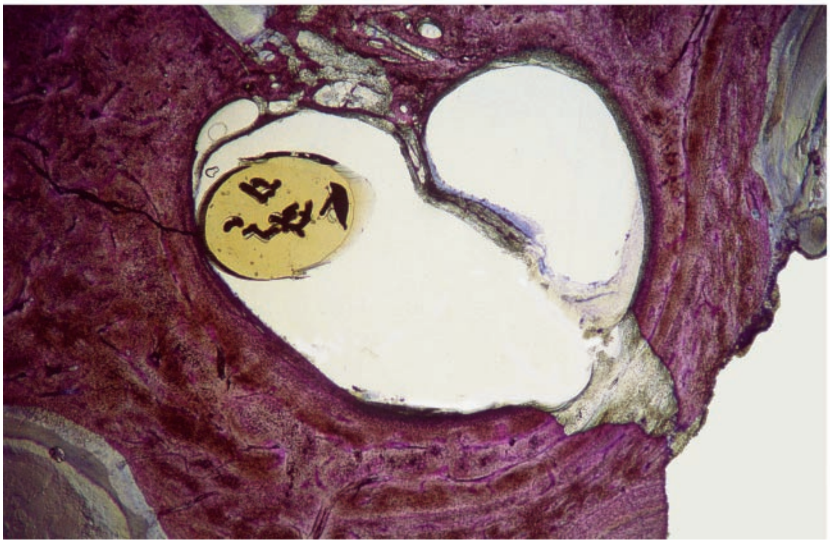

Fig. 1. Temporal bone #12: Flex*soft* array, cochleostomy antero-inferior to the round window, 23 mm surgical insertion depth, 400° histological insertion depth, no visible basal cochlear trauma. Round window membrane and basal cochlear structures are visible.

Fig. 2. Temporal bone #15: Flex^{EAS} array, cochleostomy anterinferior to the round window, 22 mm surgical insertion depth, 360° histological insertion depth, drilling cone of the cochleostomy visible, electrode enters the scala tympani atraumatically.

Fig. 3. Temporal bone #20: Flex^{EAS} electrode, 20 mm surgical insertion depth, 360° histological insertion depth. Basal grade 4 trauma – fracture of the osseous spiral lamina [13] – due to buckling of the electrode.

Fig. 4. Temporal bone #24: C40+ M electrode, 19 mm surgical insertion depth, 360° histological insertion depth, grade 4 trauma [13] due to drilling of the cochleostomy. Drilling cone visible on the lower right corner of the histological picture. Here, the cochleostomy itself causes the fracture of the osseous spiral lamina.

the result in this specimen is not representative for the evaluation of basal trauma. The other specimen showed basal trauma due to buckling of the basal end of the electrode. No further destruction of basal structures was visible in any of the remaining 6 bones. Results and implantation data are shown in table 2.

Discussion

In spite of drilling an inferior approach cochleostomy in 25 specimens, basal cochlear damage was evident in almost 50% of the bones. Anatomical variances of the cochlea (orientation of the basilar membrane within the cochlea, size of the cochlea) seemed to be at least partly responsible for this phenomenon. In a few cases (6) of specimens implanted via the cochleostomy approach, basal trauma was caused by a bulging of the electrode towards the basilar membrane adjacent to the region of the cochleostomy. This buckling seems to occur when the point of first resistance is reached and further insertion attempts are made. Histological pictures of the cochleostomy site helped to distinguish all trauma bones into either pathomechanism (direct surgical trauma or bulging of the basal electrode end).

Insertions via the round window membrane itself produced severe basal cochlear trauma in less than 15% of the temporal bones. Although drilling cannot be avoided completely when using this approach since bony overhangs have to be removed for access to the round window in many cases, no endosteal preparations in the direct vicinity of the basilar membrane are needed.

In the very beginnings of cochlear implantation, the round window approach was used to access the scala tympani [14]. Only later in the development, the cochleostomy approach was favored because a straight route to the basal cochlear turn is possible [15]. The flexibility of the array might play a central role in the selection of the right surgical approach: with a soft and flexible electrode carrier like the MED-EL arrays presented in this report, round window insertions seem to be more atraumatic, whereas for preformed or less flexible cochlear implant electrodes, a straight route of implantation into the basal turn could be less traumatic.

Up to date, several studies were dealing with the intracochlear positioning and the resulting trauma of cochlear implant electrodes [16–18]. In recent studies, the extent of cochlear trauma was assessed when implanting a two-component electrode array [19, 20]. Other concepts of perimodiolar placement of cochlear implant electrodes have been evaluated in human temporal bones, all of which showed an increased rate of cochlear trauma [21–23]. For EAS [2–4], cochlear trauma is not acceptable. Only with all intracochlear structures left intact, preservation of residual hearing is possible. In a recent paper, the intracochlear trauma of the Flex^{EAS} electrode [5], an array especially designed for use in hearing preservation for combined stimulation, was evaluated. It could be shown that this electrode carrier allows relatively atraumatic insertions. However, basal trauma occurred in some of the bones. In spite of leaving all apical structures intact, basal trauma might lead to a more widespread degeneration of the cochlear function [9].

Recently, yet unpublished data from another study group shows that when drilling a large cochleostomy, basal bulging of the electrode is much more likely to occur compared to a small cochleostomy. In our report, special emphasis was laid on the drilling of small cochleostomy diameters in all bones. This might be due to the fact that we have seen basal electrode buckling in only 6 cases even though deep insertions had been accomplished. However, basal buckling occurred in 3 of 6 deeply implanted specimens with a long Flex^{soft} electrode. This might be due to deeper intracochlear insertions with this array compared to the insertion depths of all the other electrodes used.

Conclusions

This study demonstrates a high risk of trauma to the basilar membrane and spiral osseous lamina in the basal region of the cochlea, using a cochleostomy approach, even when performed by experienced surgeons under laboratory conditions. Even though it is still unclear whether basal cochlear trauma influences apical cochlear function or not, basal trauma could have negative effects especially when performing cochlear implantations for combined EAS. Insertions through the round window membrane may offer a surgical alternative with less risk for causing basal trauma. However, forceful insertion maneuvers should be avoided in any case, as they cause buckling of the electrode and trauma to basal structures. Further studies in temporal bones and better imaging techniques of the implanted temporal bone in vivo will be helpful in determining the best surgical pathways.

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