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Long-Term Evaluation of the Effect of Intracochlear Steroid Deposition on Electrode Impedance in Cochlear Implant Patients

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Objective: To evaluate the long-term effect of intracochlear steroid deposition on electrode impedance in patients with cochlear implants.
Study Design: A retrospective study was carried out comparing the impedances of cochlear implant electrodes with and without a single application of steroids in the cochlea.
Patients: Ninety two implanted children with an average age of 5 years (range, 0.7 to 16 years) were divided in four groups according to the type of electrode and the use of steroids or not. In addition, the impedances of five children who required a reimplantation are reported.
Main Outcome Measure: The impedances of Nucleus electrodes, either straight or Contour, were measured at regular intervals up to 12 months after surgery.
Results: Two months after surgery, the impedances in the steroid groups were significantly lower than in the nonsteroid groups (straight electrodes, 3.9 versus 4.7 kOhm, respectively; Contour electrodes, 5.4 versus 6.5 kOhm, respectively). This reduction remained stable over time for the straight electrodes, but for the Contour electrodes, it seemed to disappear after 6 months. The impedances after a second implantation were significantly higher than after a first implantation (median value, 8.8 kOhm after 2 months).
Conclusions: The application of a single dose of a steroid solution reduces the electrode impedances significantly, and, for the straight electrodes, this effect seems to last. It seems justified to reimplant with caution, because this seems to increase the impedances substantially. **Key Words:** Cochlear implant impedances—Outcome—Steroids.
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In cochlear implants, the energy of the processed signals is transferred from the electrode contacts onto the nerve fiber endings through the electrode interface. One of the technical problems of cochlear implants is the electrical impedance at the interface between the electrode and the surrounding cochlear tissue. This impedance depends on the static electrical impedances of the elements involved but also on dynamic electrochemical and histologic processes at the level of this interface. High impedances lead to high voltages generated across the electrode-electrolyte interface, which may cause the current sources to saturate at low current levels and to a decreased dynamic range of the stimulation (1). Also, high voltages and a low-charge storage capacity of the electrode contacts increase the risk of irreversible electrochemical reactions at the interface, altering the composition of the tissue fluid and inducing changes in pH and the emergence of toxic reaction products (2). Finally, high impedances increase the energy consumption of the implant, which is to be avoided, especially with future developments such as totally implantable devices in mind (3).

Today's electrode designs tend to have more electrode contacts with smaller dimensions. There is also a tendency toward more space filling electrode arrays or closer contact with the modiolar tissue (modiolus hugging). These evolutions obviously will cause the intracochlear impedance of an individual electrode contact to be higher compared with larger surface and less tissue-surrounded designs. Strategies to control the impedance of the electrode interface have already been and continue to be an important issue.

There are basically two ways to improve the electrode impedance. The first is to increase the electrode surface. This is in contrast with the trend to build smaller electrodes, but a solution may be to roughen the surface. This can be done by etching, sputtering, electrochemical coating techniques, or other methods (4) and increases the

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real surface substantially without changing the diameter of the electrodes. A second way is to prevent the increase in impedance that is routinely seen postoperatively. That is speculated to be the result of two effects, namely electrochemical phenomena at the electrode-tissue interface and fibrotic tissue growth around the electrode (5). The first effect may be counteracted by electrically stimulating the electrode (6). The second effect, if it is truly attributable to reactive fibrosis, may be counteracted by steroid application, which is known to have a strong anti-inflammatory action. To test this working hypothesis, our group in Antwerp started to apply steroids in the cochlea during implantation. This fibrosis-inhibiting product should possibly lower the impact of the inflammatory reactions after electrode insertion and thus lower the electrode contact impedance (4). Guinea pigs experiments and a pilot study on patients implanted with the LAURA cochlear implant device (former Philips Hearing Implants, Edegem, Belgium) showed a 50% reduction in impedance growth when steroids were used (4). This study describes a retrospective comparative study with a longer follow-up time comparing patients who received intracochlear deposits of steroids right before insertion of the cochlear implant with subjects who did not.

MATERIALS AND METHODS

Study groups

All subjects described in this study were implanted with Nucleus 24 type implant (Cochlear Ltd., Sydney, Australia) using a soft surgery technique (7). Only children receiving their first implant and with a normal cochlear anatomy without ossification were included in the study. As shown in Table 1, four groups were defined by the type of the electrode (straight or Contour) and the use or nonuse of steroids.

The straight electrodes refer to the Nucleus 24 M or k implants and Contour electrodes to the Nucleus 24 Contour implants. All Nucleus 24 implant types have 2 large extracochlear electrode contacts: one ball contact (MP1) and one plate contact situated on the implant box (MP2). The dimensions of the intracochlear electrode contacts are different for the different types. The straight electrodes have 22 intracochlear ring contacts with average surface dimensions of 0.5 mm^2. The electrode carrier has diameter dimensions of 0.6 mm (basal) to 0.4 mm (apical). The Contour electrode also has 22 intracochlear half-a-ring contacts with average surface dimensions between 0.23 and 0.21 mm^2 (from basal to apical electrodes). The electrode carrier has diameter dimensions of 0.8 mm (basal) to 0.5 mm (apical).

The steroid test groups consist of children that were implanted in Antwerp at the University Otolaryngology Department of the St.-Augustinus Hospital. In these groups, the cochlea was perfused with a mixture of the lubricant Healon (Pharmacia Corporation, Peapack, NJ, Donnelli 1995) and the steroid product Kenacort A (1 mL of a 40 mg/mL triamcinolonacetonide solution, Bristol-Myers Squibb AG, Baar, Switzerland) just before the electrode insertion. The electrode carrier itself was also immersed in this mixture before insertion. The control groups consist of children that were consecutively implanted at the Department of Otolaryngology of the University of Nottingham. In these groups, the cochlea and electrode carrier were not lubricated at all.

It has been shown that a film of Healon on its own has no influence on the electrical impedance (8).

Table 1 summarizes the children in the different groups.

TABLE 1. *Study groups*

Electrode type	Steroids	
	Yes	No
Straight (Nucleus 24 M/k)	Test group 1 N = 24 Age, 5 yrs* (range, 0.7–16 yrs)	Control group 1 N = 30 Age, 5 yrs* (range, 2–11 yrs)
Contour (Nucleus Contour)	Test group 2 N = 20 Age, 5 yrs* (range, 0.7–13 yrs)	Control group 2 N = 18 Age, 5 yrs* (range, 2–14 yrs)

*Average age.

Cases

In addition to these group data, five case studies were included in this study. These five children were reimplanted with a Nucleus 24 implant after device failure of their first implant (LAURA flex type, former Philips Hearing Implants, Edegem, Belgium). All of them received intracochlear deposits of the Healon-Kenacort A mixture at the time of their first implantation as well as at the time of reimplantation. Table 2 describes these cases in terms of age at first implantation, age at reimplantation, and reimplanted device type.

Methods

Impedance measures were done by delivering biphasic pulses using a 25-μs phase width and a current level of 100 units CL (approximately 85 μA). Voltages created between the stimulated electrode contacts were measured and registered using back telemetry. A detailed description of this technique was published elsewhere (9). Briefly, radiofrequency bursts are sent from the speech processor to the implant, the implant returns coded information to the programming system about the voltage developed on the electrode during stimulation, and these voltages are measured at four points on the stimulus waveform and are encoded as four pairs of radiofrequency pulses; the time interval between each pair is proportional to the measured peak-to-peak voltage created across the electrode interface.

The Nucleus 24 implant system allows stimulation and impedance measurements in the following four different modes: 1) common ground (CG) mode, where the impedance is measured between an intracochlear electrode contact and all other intracochlear electrodes coupled in parallel; 2) monopolar 1 (MP1) mode, where the impedance is measured between the intracochlear electrode contact and an extracochlear ball elec-

TABLE 2. *Individual patients*

Case	Device type (all Nucleus)	Age at first implantation (yrs)	Age at reimplantation (yrs)
1	24 Contour	2	6
2	24 Contour	4	7
3	24 Contour	4	11
4	24 M	9	16
5	24 Contour	13	17

trode situated at the temporal muscle; 3) monopolar 2 (MP2) mode, where the impedance is measured between the intracochlear electrode and an extracochlear electrode plate situated on the implant box under the skin; and 4) monopolar 1 + 2 (MP1 + 2) mode, where the impedance is measured between the intracochlear electrode and MP1 and MP2 coupled in parallel. In all patients, CG, MP1, MP2, and MP1 + 2 impedances were measured. MP1 + 2 impedances are relevant because this is the routine stimulation mode of the implant. On the other hand, CG impedances reflect better the purely intracochlear resistance/capacitance, and this is what the steroids are expected to interfere with. Because the intracochlear impedances can be suspected to be orders of magnitudes higher than the extracochlear impedances, it can be anticipated that the CG impedance corresponds well with the MP1 + 2 impedance, the first only differing from the second by a small negative constant that represents the extracochlear impedance. To verify this, a linear regression analysis was performed on paired CG-MP1 + 2 measures taken from 4328 individual electrode contacts from test group 1.

Impedance measures for the groups were made at the following different time intervals: 1) intraoperatively, immediately after the electrode insertion in the cochlea; 2) 3 to 4 weeks after implantation, just before the first fitting; 3) 3 to 4 weeks after implantation, after the first fitting; 4) 2 months after implantation; 5) 3 months after implantation; 6) 6 months after implantation; and 7) 12 months after implantation.

To verify whether the extracochlear impedances change over time, linear regression analysis was performed on 528 paired CG-MP1 + 2 measures from test group 1 in period 2 and compared with a similar analysis on the data from periods 5 and 7.

For all cases, impedance measures were available for the same intervals at up to 6 months of follow-up. Their results are also expressed in terms of percentile value referring to their nonreimplanted peers.

Statistical analysis

Shortcut or open-circuit electrodes are not considered for data analysis, because these contacts are not operational contacts and thus not stimulated. The upper and lower boundaries for an electrode contact to be functional have been determined by the manufacturer to be, respectively, 0.7 and 20 kOhm.

Linear regression statistics were used to determine the relationship between CG and MP1 + 2 impedance values for paired measures. To check for normality of the data distribution, a Shapiro-Wilks W test was performed on all group data series.

For normally distributed group results, paired t tests with a significance level of 0.05 were used to compare dependent data, such as impedance measures at the different time intervals. For the groups that are not normally distributed, Wilcoxon tests for paired data were used. For independent data, normal t tests were used to compare between normally distributed group data and Mann-Whitney U tests for not normally distributed group data.

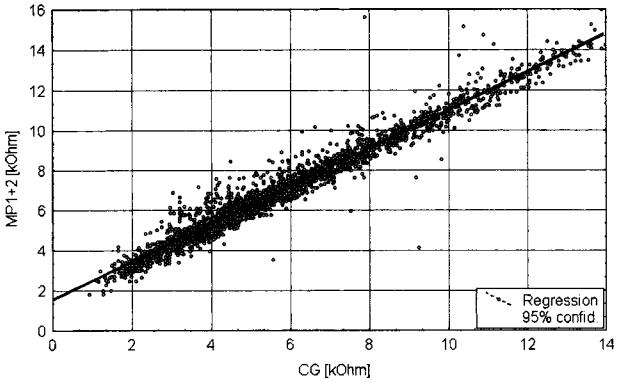

FIG. 1. Linear regression analysis plot of paired MP1 + 2-CG impedance measures of 4328 electrode contacts.

RESULTS

Linear regression statistics performed on the 4328 paired CG-MP1 + 2 impedance measures show a highly significant linear correlation between the MP1 + 2 impedance and the CG impedance ($R^2 = 0.96$; $p < 0.00001$ Fig. 1). MP1 + 2 always tends to be 1.55 kOhm greater then CG impedance ($\text{impedance}_{MP1+2} = 1.55 + 0.96\ \text{impedance}_{CG}$). The intracochlear impedance thus accounts for the major part of the MP1 + 2 impedance, as expected (see Material and Methods). The intercept of the linear regression line from the 520 paired CG-MP1 + 2 impedance measures (group 1) remained very stable over time (1.55 kOhm for the prefitting measures, 1.43 kOhm 3 months after implantation, and 1.46 kOhm 12 months after implantation). All but six data series passed the Shapiro-Wilks W test for normality ($p \geq 0.05$) (22 of 28).

Group data

All group data are summarized in Table 3 in terms of mean and standard deviation and in Figure 2 in terms of mean and standard error of the mean. At the time of the operation, the impedance tended to be higher for the test groups compared with their control groups (4.57 versus 3.83 kOhm for groups 1 and 8.33 versus 6.82 kOhm for

TABLE 3. *Impedances of the study groups over time (kOhm)*

Group	Intraoperatively	Prefitting	Postfitting	2 mo	3 mo	6 mo	12 mo
Test group 1	4.57 ± 1.42	5.31 ± 1.56	4.41 ± 1.10	3.94 ± 0.89	3.94 ± 0.67	4.15 ± 0.76	4.49 ± 0.71
Control group 1	3.83 ± 1.54	6.58 ± 1.09	5.01 ± 1.05	4.71 ± 0.80	4.59 ± 0.80	4.85 ± 1.17	5.10 ± 1.20
p value (t test)	0.07	0.001	0.07	0.005	0.003	0.04	0.04
Test group 2	8.33 ± 1.27	8.62 ± 2.16	5.98 ± 1.70	5.43 ± 1.15	5.37 ± 1.12	5.65 ± 1.42	5.68 ± 1.34
Control group 2	6.82 ± 1.67	9.59 ± 1.17	7.16 ± 1.23	6.52 ± 1.41	6.10 ± 1.10	5.55 ± 0.88	5.35 ± 0.96
p value (t test)	0.003	0.1	0.02	0.02	0.05	0.8	0.7

Mean and standard deviation of CG impedance for the different groups under study and for the different evaluation periods. Group definitions are given in Table 1.

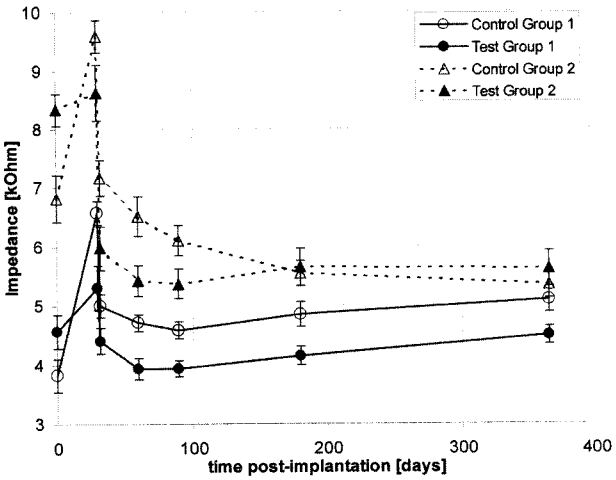

FIG. 2. CG impedance values as a function of the postoperative time for the different study groups. The different symbols represent the mean values; the error bars represent the standard error of the mean.

groups 2). This difference was not significant ($p = 0.07$) for groups 1 but was significant for groups 2 ($p = 0.003$).

In all series, the impedance values reached their maximal values at the time before the first fitting. There was a significant difference between test and control group 1 ($p = 0.001$) but not between test and control group 2 ($p = 0.1$). The rise in impedance postoperatively was significantly higher in the control groups compared with test groups (2.75 versus 0.74 kOhm for groups 1 and 2.77 versus 0.29 kOhm for groups 2, $p < 0.05$).

At the second fitting session, impedances dropped significantly in all four groups. The decrease was 0.91 and 1.57 kOhm for test and control group 1, respectively, and was even greater for test and control group 2, where it was 2.64 and 2.43 kOhm, respectively. The values for the test groups remained lower than for the control groups but were not significantly different ($p = 0.07$ for groups 1 and $p = 0.02$ for groups 2).

Impedances continued to decrease (2 months postoperatively) in all groups, and all except control group 2 attained their minimal values 3 months after implantation. The differences between test and control group were significant for the 2- and 3-month evaluation times ($p < 0.05$).

In test and control groups 1, impedance tended to increase from the 3-month to the 6- and 12-month evaluation times. In these groups, the differences between test and control groups remained almost equal and significantly different until the end (12 months) of the follow-up ($p < 0.05$).

In groups 2, impedance tended to increase slightly for test group 2 but seemed to decrease additionally for control group 2 until 6 months after implantation. The differences between test and control group 2 seemed to disappear for the 6- and 12-month postimplantation times ($p = 0.8$ and 0.7, respectively).

Case data

The results of the five reimplanted cases are given in Table 4 and shown in Figure 3. For all postfitting evaluation periods, the intracochlear impedances were significantly higher compared with their nonreimplanted peers ($p < 0.05$). This was true in all cases except case 3, in which the impedance lay within the range of its nonreimplanted peers.

DISCUSSION

The intracochlear impedance has been shown to account for the major part of the MP1 + 2 impedance. The extracochlear part of the overall MP1 + 2 impedance is small (1.5 kOhm) and seems to vary very little over time.

The intracochlear impedance changes over time. Part of this is attributable to the electrical stimulation. This is most clearly seen when comparing the values just before the onset of the stimulation (during the first fitting) and a couple of weeks later. This shows a dramatic decrease in impedance in all groups. Such an effect was already reported earlier (10) and is also known from pacemaker stimulation (6).

Another part of the impedance changes over time is thought to be attributable to reactive fibrosis at the site of the electrodes. This would contribute in a negative sense to the impedances, and it is worthwhile trying to reduce this effect. Because steroids are known to strongly inhibit the reactive processes of inflammation and scar formation, it would make sense applying these drugs to try to

TABLE 4. *Impedance data [kOhm] for the five reimplanted patients*

Case	Intraoperatively	Prefitting	Postfitting	2 mo	3 mo	6 mo
1	15.19	13.40	11.83	10.78	10.97	11.43
	<P1	=P1	<P1	<P1	<P1	<P1
2	10.80	10.33	9.34	8.92	9.58	9.15
	=P3	=P20	=P2	<P1	<P1	=P1
3	7.59	3.59	4.05	4.22	4.24	3.82
	=P30	=P1	=P10	=P10	=P20	=P10
4	6.43	9.66	9.25	9.64	10.92	8.49
	=P10	<P1	<P1	<P1	<P1	<P1
5	10.54	11.11	8.70	8.21	10.80	7.71
	=P4	=P10	=P5	=P1	<P1	=P7

P values: percentile value of the case data points in the distribution of their nonreimplanted peers.

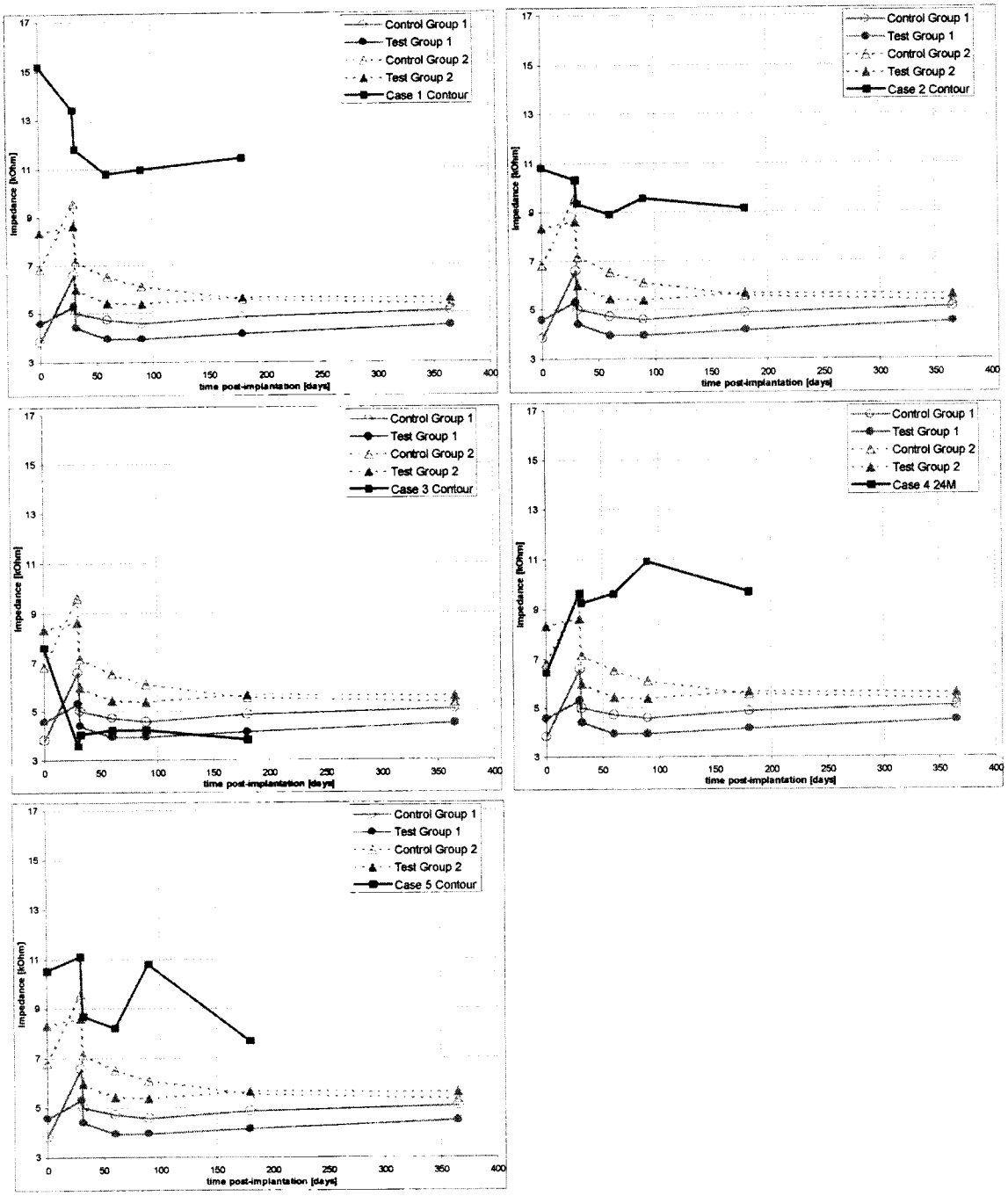

FIG. 3. CG impedances of the five reimplanted cases (black) and the group data from Table 3 (grey).

interfere with the postoperative impedance growth. This study evaluates the effect of a single administration of steroids, applied locally in the cochlea at the time of implantation.

A first conclusion that can be drawn from this study is that the perfusion of the cochlea with a turbid mixture of Healon and Kenacort A causes an immediate increase of the intracochlear intraoperative impedance. This is true for both the large Nucleus M and k electrodes and the small Contour electrodes. A possible explanation may be the introduction of more air bubbles by mixing the two components or an intrinsic lower conductivity of the mixture. It has been shown that a film of Healon on its own has no influence on the electrical impedance (8).

A second conclusion is that the impedances increase during the first weeks after surgery, as long as the implant has not been turned on, and that this increase is smaller when steroids are used. Thus, after a couple of

weeks, the impedances in the steroid groups are significantly smaller than in the other groups ($p < 0.05$). This difference in impedance between the test and control groups will be referred to as the steroid effect. Indeed, it was shown earlier that the use of Healon alone does not contribute to this effect. It was reported earlier in a similar study comparing the impedances after applying a Healon/steroid mixture (Antwerp group) with impedances after applying Healon alone (Melbourne group) that similar differences could be found (De Ceulaer et al., unpublished data, 2000). In consequence, the fact that the electrodes in the control groups in this study were not lubricated with Healon is probably not important.

A third conclusion is that this steroid effect lasts at least 12 months when the larger electrodes are used. In fact, over time, the impedance curves for test and control group 1 tend to run parallel from the second fitting until the end of the follow-up. If the steroid effect is attributable to the anti-inflammatory effect of the steroids, it may seem difficult to explain such a long-term effect after a single application of the drug. But the authors speculate that the traumatic event as such is also limited in time (only the introduction of the electrode), and in consequence, no inflammatory reaction is to be expected later on. The single dose of steroids may very well suffice to prevent or decrease the immediate inflammation attributable to the surgical insertion of the electrode. In this study, the electrode insertions were performed at different locations by different surgeons. Although this may have an effect, the same differences in impedance growth were observed in a similar study using the LAURA cochlear implant device (4). In that study, the same surgeon implanted both the subjects that received steroids as well as the subjects that did not.

A fourth conclusion is that this steroid effect may not last as long when the Contour electrodes are used. This group is smaller in number, so more data are needed. Still, it is remarkable not only that the impedances are higher, which is probably attributable to the smaller surfaces, but also that the steroid effect seems to fade out 6 months after implantation. The authors did not expect the steroid effect to disappear in group 2 6 months after implantation, and it remains unclear how to explain this. One interpretation could be that with the Contour electrodes, the fibrosis remains active during the months after surgery. A single administration of steroids would then have an immediate effect (as is the case), but this effect would disappear over time and the fibrosis would go on. Why the fibrosis would continue with a Contour electrode and not with the straight electrodes of the Nucleus 24 M and k types remains a matter of speculation. The modiolus-hugging design, with a close and permanent contact between the electrodes and the modiolus, could play a role in this phenomenon.

A final conclusion relates to the reimplantations. Four of five patients who required a new implant because of failure of the former implant showed significantly higher impedances than the "virgin" peers, and these high impedances remained high during the 6-month follow-up after the reimplantation. This is most likely attributable to the additional trauma of the second intervention. Although the group is too small and the follow-up too short for definite conclusions, this could become an important issue for the future. Especially children, who will probably need more than one implant in their life, may experience problems with the second or third implant if the impedances become too high. Both the implant surgeon and the manufacturer should take this possibility into account. A direct correlation between electrode impedance and patients' performance was not a topic in this study. Patients' performance depends on a multitude of preoperative, intraoperative, and postoperative factors, whereas increased electrode impedance can technically be overcome in most cases by using current sources.

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