PREDICTION OF MECHANICAL EFFECT DUE TO A COCHLEAR IMPLANT
ABSTRACT

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The effect of a cochlear implant on residual, low frequency, hearing is complex and poorly understood. This research focuses on the mechanical effect of a cochlear implant on the cochlear mechanics by comparing the predicted basilar membrane, BM, response before and after the implantation. Audiograms measured from pre- and post-implant users are used as input of a computational model of the passive cochlea, proposed by Elliott *et al.* (Elliott *et al.*, 2011), which are then used to study the mechanical effect of the implantation. In the model, a short cochlea implant, designed to electrically stimulate the basal regions at high frequencies while allowing normal hearing at low frequencies (Cochlear, 2008), is introduced into the lower cochlear fluid chamber. The active amplification of the cochlea is not considered, since a passive cochlear model whose response is not dependent on stimulus level can reasonably well represent the cochlea for subjects with hearing impairment. The results for the BM coupled response show that the volume change in the fluid chambers due to the implant has a negligible effect, less than about 0.1 dB, on the vibration of the modeled cochlea at low frequencies. A more extreme condition, in which the cochlear implant is assumed to touch the BM at some or whole basal positions and thus impeded its motion, is also studied. Although no travelling wave can propagate in the basal region in the latter case, the remainder of the cochlea is still coupled to the stapes by incompressible fluid. The BM response at low frequencies is relatively unaffected by the blocking of the BM motion in the basal region, although the effect is more dramatic for excitation frequency whose characteristic place is close to the end of the implant. Although this work does not model every aspect of the cochlear implantation, it does provide a way of predicting the possible mechanical effects of the implantation on the cochlear passive mechanics and the residual hearing.

Keywords: Cochlear model, cochlear implant, mechanical effect.

1. INTRODUCTION

There are 360 million people worldwide who have disabling hearing loss and an estimated 9 million of those are in the UK (WTO, 2014). Over 180, 000 people worldwide have received a cochlear implant (CI), which is a surgically implanted electronic device that provides a sense of sound to a person who is profoundly deaf or severely hard of hearing, with approximately 10,000 recipients in the UK (UK, 2008). The effect of a cochlear implant on residual, low frequency, hearing is, however, complex and poorly understood.

With an increasing number of cochlear implant patients, a model that is able to predict the possible effects on the hearing level before and after surgery will be particularly useful to clinicians. Cochlear implant candidates by definition have very little measurable hearing, thus can be assumed to have lost cochlear active amplification function. Figure 1 shows average hearing threshold measured from 200 CI users before and 2 months after surgery (A.E. Causon *et al.*, 2014) when the CI is not turned on. It can be found that for most mid- and high-frequency regions, the minimum detectable hearing (MDH) is greater than 80 dB. The overall effect of a CI is an increase of the MDH value about 25 dB for low frequencies and less than 5 dB for high frequencies. The reason for this reduction of residual hearing is complex and dependent on many factors such as operation method, patient's condition etc. The volume change of the cochlear fluid and mechanical interference to the basilar membrane (BM) due to a cochlear implant could play a role in the reduction of residual hearing after implantation, which has not been studied so far.

In this paper, we present an initial work using a simple passive model of the cochlea to predict the possible mechanical effects due to a cochlear implant on residual hearing and the cochlear response.

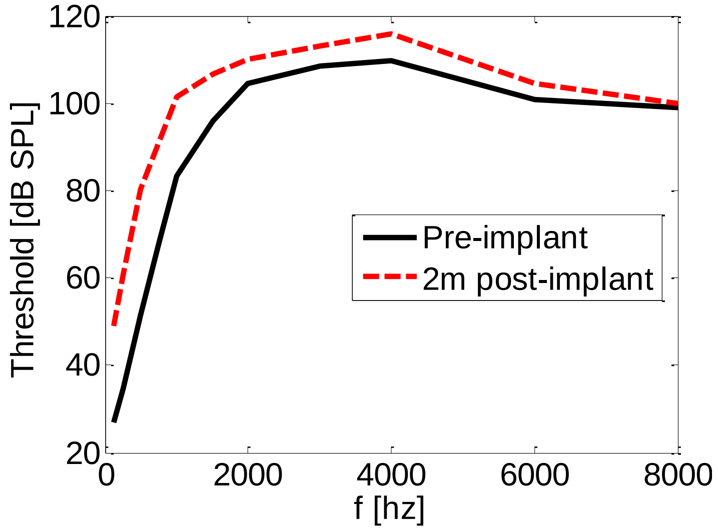

Figure 1 Average value of hearing threshold measured from pre- and post-implant (2 months later after surgery without turning on the cochlear implant) users. Data was provided by A.E. Causon (A.E. Causon *et al.*, 2014).

2. AN ELEMENTAL MODEL OF THE PASSIVE COCHLEA

The coupled behavior of the linear cochlear dynamics can be represented by a model that is dependent on only a single dimension by the definition of a radially-averaged basilar membrane (BM) velocity, as described by Elliott *et al*. (Elliott *et al.*, 2011). This linear cochlear dynamics can be split into two components: the way that the pressure distribution is determined by the fluid coupling within the cochlear chambers when driven by the BM and stapes velocities, and the way in which the BM dynamics respond to the imposed pressure distribution. In this model, the BM dynamics are represented by a series of isolated mass-spring-damper systems, as shown in Figure 2, whose natural frequency is adjusted to match the frequency map of the human cochlea.

If the single longitudinal variables for modal pressure difference and modal velocity are spatially sampled as finely as required, for example at least six elements within the shortest wavelength present (Fahy and Gardonio, 2007), dividing the cochlea into N segments, we can define, at a single frequency, the vectors of complex pressures and velocities at these discrete locations, **p** and **v**, to be

$$\mathbf{p} = \left[p(1), p(2), \cdots p(N) \right]^{\mathrm{T}}, \ \ \mathbf{v} = \left[v(1), v(2), \cdots v(N) \right]^{\mathrm{T}}. \qquad (1)(2)$$

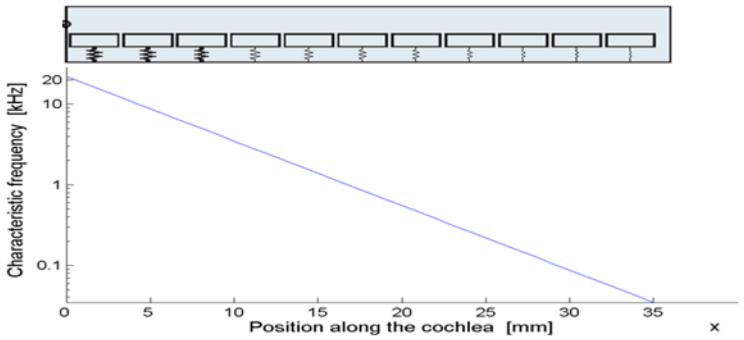

Figure 2 Idealised representation of the inner ear representing the BM as a series of mass-spring-damper systems distributed along the cochlea, together with the natural frequency distribution of these single degree of freedom systems.

The BM, however, is assumed only to extend from element 2 to element $N - 1$. The first element of $\mathbf{v}$, $v(1)$**,** is the normalized stapes velocity, defined as the stapes volume velocity divided by the elemental area, $W\Delta$, where Δ is the length of an element in the x direction, which is equal to L/N where L is the overall length of the cochlea. The final element, N, is used to account for the behavior of the helicotrema. This is assumed to equalize the pressure in the two chambers at the end of the cochlea so that $p(N)$ is zero. The vector of pressures due to the vector of stapes and BM velocities can be written as

$$\mathbf{p} = \mathbf{Z}_{\mathrm{FC}}\mathbf{v}, \tag{3}$$

where $\mathbf{Z}_{\mathrm{FC}}$ is a matrix of impedances due to the fluid coupling. The vector of BM velocities can also be written as

$$\mathbf{v} = \mathbf{v}_{\mathrm{s}} - \mathbf{Y}_{\mathrm{BM}}\mathbf{p}, \tag{4}$$

where $\mathbf{v}_{\mathrm{s}}$ is a vector whose first element is equal to the normalized stapes velocity, u_{s}, unloaded by the pressure in the cochlea, with all other elements being zero. $\mathbf{Y}_{\mathrm{BM}}$ is a matrix of BM admittances, although the first diagonal element can be used to represent the admittance of the middle ear, via the oval window, and thus account for loading of the stapes by the pressure, $p(1)$, at the base of the cochlea.

Equations (5) and (6) can be combined to give a simple expression for the vector of BM velocities in the coupled cochlea as

$$\mathbf{v} = \left[\mathbf{I} + \mathbf{Y}_{\mathrm{BM}}\mathbf{Z}_{\mathrm{FC}}\right]^{-1}\mathbf{v}_{\mathrm{s}}, \tag{5}$$

where $\mathbf{v}_{\mathrm{s}}$ is the known input driving the stapes. Thus, once the form of $\mathbf{Y}_{\mathrm{BM}}$ and $\mathbf{Z}_{\mathrm{FC}}$ have been determined, the coupled response for a given stapes velocity can be readily calculated using simple linear algebra.

Figure 3 shows variations of cross-sectional area of the two fluid chambers, scala vestibule (SV), A_1, scala tympani (ST), A_2, and modified scala tympani, A_2', when a short cochlear implant is included, along the length of the human cochlea, together with corresponding assumed variations in the width of the fluid chamber, *W*, and BM width, *B*. In this model, the scala media (SM) is assumed to be merged into the SV, since the Reissner's membrane that separates the SM from SV is often assumed to be "acoustically transparent" having no influence to the cochlear mechanical functions (Dallos *et al.*, 1996). These variations are based on data given by Zakis and Witte (Zakis and Witte, 2001), which are interpolated using a cubic spline function and are reasonably consistent with the measurements of Thorne *et al.* (Thorne *et al.*, 1999) and the earlier estimates provided by Fletcher (Fletcher, 1958) and Zwislocki (Zwislocki *et al.*, 2003).

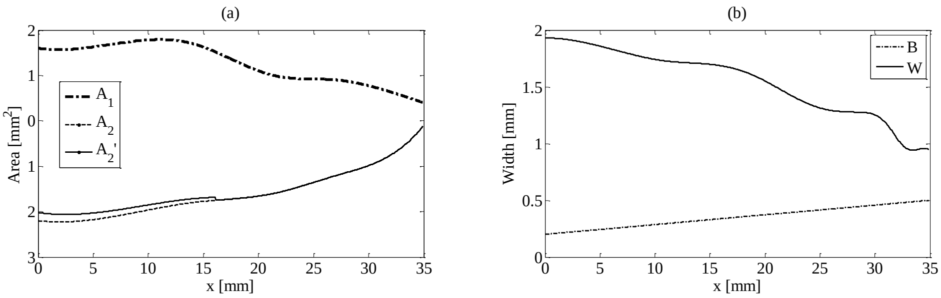

Figure 3 Assumed variation (a) in the cross-sectional area of the upper, A_1, and lower, A_2, fluid chambers as a function of longitudinal position in the asymmetric model, together with a modified area of the lower chamber, A_2', when a CI is inserted, and (b) the assumed variation in the width of the cochlear partition, *W*, and BM width, *B*.

MECHANICAL EFFECT OF A COCHLEAR IMPLANT ON THE BM RESPONSE

Figure 4 shows the calculated distribution of the coupled BM velocity calculated using the model described in Section 2. The assumed input driving the stapes, $\mathbf{v}_{\mathrm{s}}$, is based on the measured pre-implant hearing threshold shown in Figure 1. In this condition, a short cochlea implant is introduced into the lower chamber, having a length of 16 mm with an area tapering from 0.18 mm^2 down to 0.07 mm^2. These dimensions are based on the Cochlear Hybrid™ implant (Cochlea, 2008), which is designed to electrically stimulate the basal regions at high frequencies while allowing normal hearing at low frequencies, further along the cochlea. The results for the coupled response, with and without the effect of implant on the cochlear fluid volume, differ by less than 0.1 dB and cannot be distinguished on the scale of Figure 4, indicating that this small change in area has a negligible effect on the passive behavior of the modeled cochlea at frequencies simulated. The volume of the implant needs to be made about ten times larger than that assumed above for the response to change by 1 dB, and this change then only occurs for the response at about 2 kHz, whose characteristic place is closest to the end of the implant.

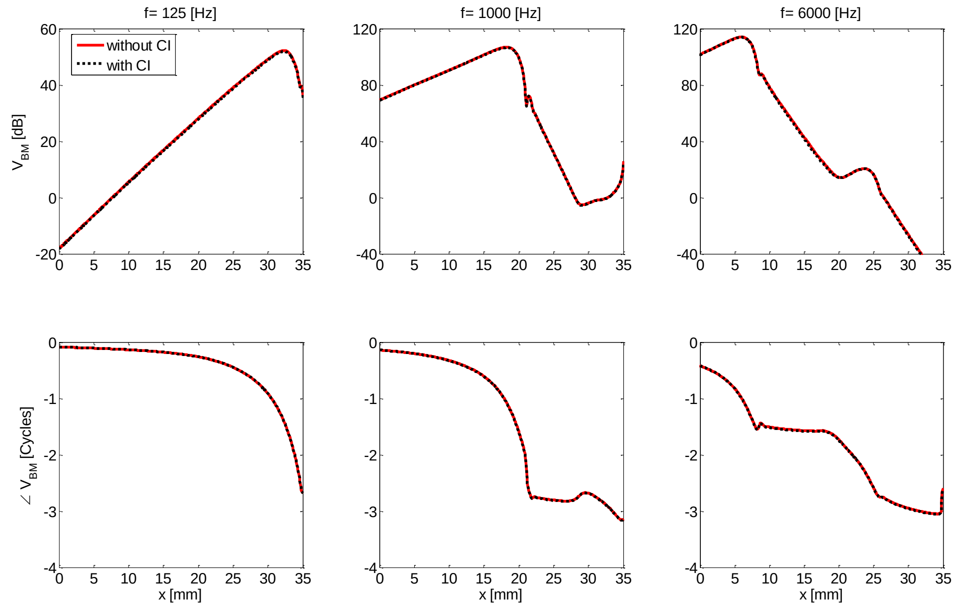

Figure 4 Coupled BM velocity distribution in the model at frequencies of (a) 125 Hz, (b) 1 kHz and (c) 6 kHz with the excitation amplitude assumed to be equal to the pre-implant hearing threshold at each corresponding frequency shown in Figure 1, when the volume of the fluid chamber is assumed to be changed due to insertion of a short cochlear implant (dashed line). Also shown, for reference, (solid line) are the distributions without the cochlear implant.

Figure 5 shows the coupled BM velocity in the condition that part of the BM, 5 mm in this example, is assumed to be blocked due to the cochlear implant. It can be seen that at low frequency when the blocked part is far away from the characteristic place, the coupled BM velocity is barely affected by the CI, except the blocked region. When the blocked part is close to the characteristic place, at 1000 Hz in this example, the peak of the BM velocity is surprisingly increased by about 10 dB. If the blocked part is beyond the characteristic place, there is no significant change to the coupled BM velocity basal to the peak. This may explain that high frequency residual hearing is less affected by the CI, as shown in Figure 1.

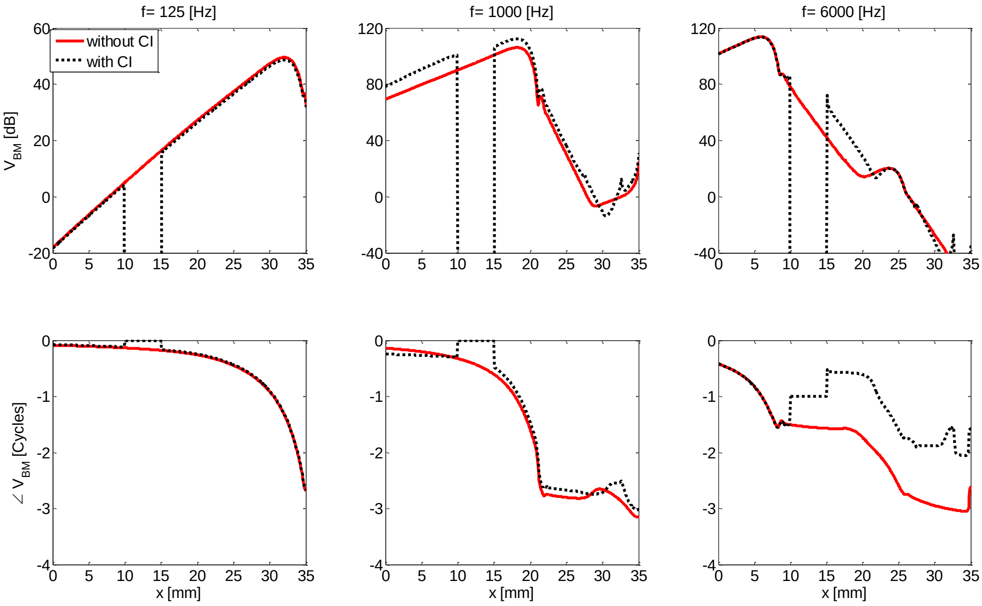

Figure 5 Coupled BM velocity distribution in the model at frequencies of (a) 125 Hz, (b) 1 kHz and (c) 6 kHz with the excitation amplitude assumed to be equal to the pre-implant hearing threshold at each corresponding frequency shown in Figure 1, when the BM motion is assumed to be partially blocked due to the inserted short cochlear implant (dashed line). Also shown, for reference, (solid line) are the distributions if the BM motion is not blocked.

A more extreme effect would be expected if the cochlear implant touched the BM at some basal positions, and thus blocked its motion. In order to explore the consequences of this effect, another condition has been simulated in which the cochlear implant is assumed to completely block the motion of the BM all the way along its 16 mm length by setting the BM admittance to be zero for these corresponding BM elements. In this extreme condition, although the cochlear travelling wave cannot now propagate in the basal region, the remainder of the cochlea is still coupled to the stapes by incompressible fluid columns. The travelling wave now starts from 16 mm along the cochlea, as seen in the phase responses, but is relatively unaffected by the blocking of the BM motion for low frequencies excitation. For these low frequencies simulations, the passive cochlear model, however, may not represent the reality well since the measured hearing threshold is about 40 dB, as shown in Figure 1, indicating the cochlear active amplification is functional. This suggests an active cochlear model would be desired for these low frequency regions.

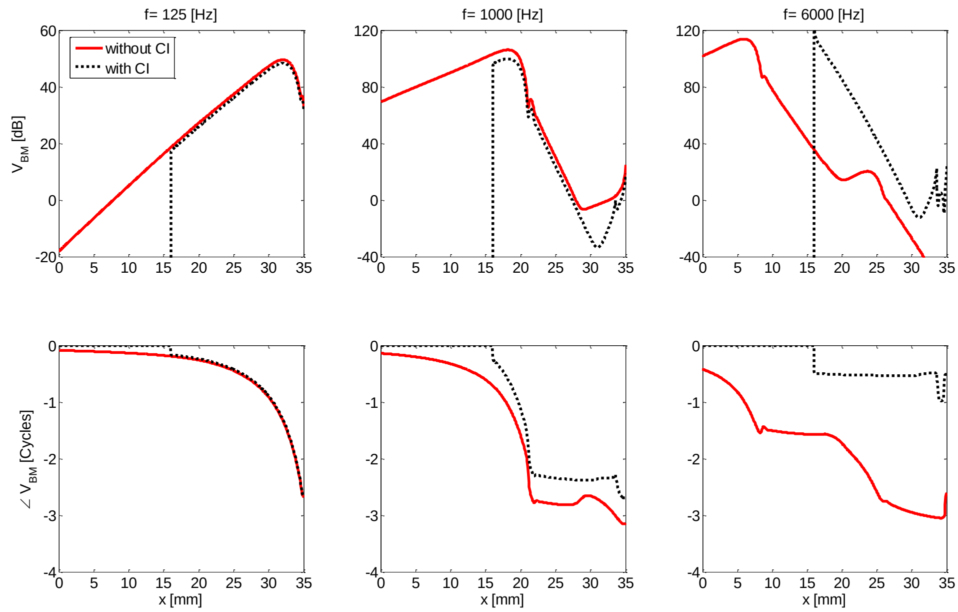

Figure 6 Coupled BM velocity distribution in the model at frequencies of (a) 125 Hz, (b) 1 kHz and (c) 6 kHz with the excitation amplitude assumed to be equal to the pre-implant hearing threshold at each corresponding frequency shown in Figure 1, when the BM motion is assumed to be blocked along the entire length of a short cochlear implant (dashed line). Also shown, for reference, (solid line) are the distributions if the BM motion is not blocked.

The effect is more dramatic for excitation frequency whose characteristic place is close to and beyond the end of the implant. The peak response for the BM velocity, for example at 1000 Hz, shows a reduction about 5 dB which is similar to the measured data. For frequencies higher than the characteristic frequency whose characteristic place is close to the end of the CI, the BM peak response is no longer corresponds to its characteristic place and is, surprisingly, much greater than the response from the unblocked model.

CONCLUSION

The effect of a cochlear implant on residual hearing is an important clinical topic, but yet to be understood. This initial work predict some possible mechanical effects due to a cochlear implant on the cochlear response, thus the residual hearing using a simple passive cochlear model. The fluid volume change due to the implant plays a negligible role in affecting the passive BM response, less than 0.1 dB, at low frequencies. If the BM was partially blocked by the cochlear implant, the effect of this mechanical interference to the peak of the BM velocity is predicted to be small, except when the blocked part is close to the characteristic place from the basal end, in which case the peak is surprisingly increased by about 10 dB. The change of the BM dynamics due to the interface of the implant, especially when the BM is entirely blocked by the implant, is predicted to dramatically affect the cochlear response at frequencies higher than the characteristic frequency corresponds to the characteristic place close to and beyond the end of the implant.

Although this passive model of the cochlea does not represent the every aspect of the cochlea with implantation, it does provide a way of predicting the possible mechanical effects of the implantation on the cochlear passive mechanics and the residual hearing. This work cannot explain 25 dB drops in sensitivity at low frequencies, as shown in Figure 1, but it clearly shows that there must be other, presumably physiological, reasons cause this damage to the residual hearing. In the further work, the cochlear active amplification will be introduced into the model and may provide a better representation of the residual hearing and furthermore a better prediction of the mechanical effect of a cochlear implant at low frequencies.

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AUTHOR CONTRIBUTIONS

Guangjian Ni: Propose the work on studying mechanical effect of a cochlear implant, co-author of the paper (Elliott *et al*., 2011), in which the cochlear model used here was proposed, performed all the numerical simulations and wrote up the manuscript.

Stephen J. Elliott: First author of the paper (Elliott *et al*., 2011) that originally proposed the cochlear elemental model; provide guide on simulation design and manuscript writing.

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