The lessons of middle-ear function in non-mammals: improving columellar prostheses

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Summary

Due to the simplicity of their manufacture and placement, middle-ear prostheses are generally constructed using only a single 'ossicle'. The variety of pathologies frequently make it necessary to devise individual solutions and the results are often unsatisfactory. Many methods of improving the prostheses have been tried, with very mixed results. Even until recently, the fundamental assumptions underlying the use of single-ossicle, or columellar, prosthesis have been questioned, with suggestions that this type of prosthesis should be abandoned in favour of attempts to reconstruct a true three-ossicle middle ear[1]. As some of the assumptions in the literature regarding columellar middle ears are incorrect and some published information is not easily accessible, a brief review of pertinent details of non-mammalian systems is given here.

INTRODUCTION

The essential features of the functional differences between one-ossicle and three-ossicle middle ears have long been known[2–5]. The data are very important in assessing whether a new approach should be taken towards constructing middle-ear prostheses, as Mills[1] proposes, or not. Pertinent comparative facts concerning the function of the middle ear are outlined below.

In both non-mammalian (one ossicle, or columellar middle ears) and mammalian (three-ossicle middle ears), three separate amplification mechanisms exist:

(1) The *difference in area* between the tympanic membrane and the footplate of the columella or stapes. There is no difference between birds and mammals in this feature[6]. This amplification factor is highly frequency dependent and the effective area of the tympanic membrane falls towards higher frequencies due to the increasing complexity of the phase relationships across the vibration pattern on the tympanic membrane. This is true of both types of middle ear[2,7].

(2) The *lever action* between malleus and incus in mammals (first-order lever) and within the extracolumella in non-mammals (second-order lever). The effectiveness of these two lever systems is equally good at frequencies below about 5 kHz[3–5].

(3) The *curved-membrane* amplification[8]. The effect of this amplification factor is also highly frequency dependent[7]. It is also effective in both types of middle ear, even though the non-mammalian tympanic membrane curves outwards, instead of being concave as in mammals.

In view of these functional similarities, at least up to 5 kHz, and thus covering those frequencies most important for speech perception and music appreciation, there is no *a priori* reason to favour one middle-ear type over the other as a model for prostheses. Instead, considerations of simplicity of form, ease of manufacture and of surgical placement must pre-dominate. At least in cases of total replacement, the columellar ossicle system is certainly simpler to construct and install, especially if one considers the difficulty of achieving an appropriate suspension of the three-ossicle system *in situ*.

HOW COULD A COLUMELLAR PROSTHESIS BE OPTIMIZED?

Mills[1] correctly noted that it would be difficult to reproduce the convex shape of the avian tympanic membrane. However, it is equally, or even more difficult to reproduce the tension in the concave mammalian tympanic membrane. Whether a convexity or concavity is present, the important feature is probably only the presence of a mild tension on the membrane to optimize transmission of sound. Compared to the steady displacement produced by this mild pressure, the displacements produced by even the loudest sounds are negligible (maximally 1 μm at the stapes at 100dB sound pressure level), so there is no need to fear 'the ossicle being driven into the cochlea by acoustic stimuli'[1]. However, probably no prostheses will be able to

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reproduce the curved-membrane lever contribution to middle-ear impedance matching (because of the problems associated with setting up and maintaining the correct membrane tension) and considerations of this problem do not help to determine the best ossicular system. Instead, it is necessary to try to optimize the other two factors involved in middle-ear impedance matching. Of these two, it will also be difficult or impossible to change the relationship between the area of the reconstructed tympanic membrane and that of the footplate. Thus there remains only one feature that could be improved and that is *the lever ratio*.

LEVER RATIO

The second-order lever in non-mammalian middle ears functions because the point of insertion of the columella into the extracolumella is not at the extracolumella tip, but at some point between the tip and the fulcrum at the edge of the tympanic membrane[2,6]. This results in a lever ratio of two or three to one[2–4]. In order to take advantage of this, reconstructions should therefore pay attention to the following features;

(1) An elastic element should be attached to the eardrum prosthesis. This is referred to here, as it is in non-mammals, as the 'extracolumella'. The shaft of the columellar prosthesis and the portion of the extracolumella in contact with the tympanum should be quite stiff, as if they were ossified. The material by which they are joined, however, should be flexible, like cartilage. The insertion of the columellar shaft into the extracolumella can be stabilized in the tympanic membrane by adding supports that go off at angles along the inner face of the tympanic membrane, as in non-mammalian middle ears[4] (Chap 3).

(2) The columella shaft should *not* insert on the extracolumella in the middle of the tympanic membrane, otherwise there will be no lever action. The further the insertion point is moved towards the edge of the tympanic membrane, the greater will be the lever action. Using appropriate materials, a lever ration of 3 (insertion point two-thirds of the way from the tip of the eardrum towards the edge of the eardrum) should be achievable and would be reasonable. This lever ratio, together with the area ratio, should provide good impedance matching at least up to several kilohertz.

Taking these features into account would produce an improved middle-ear prosthesis, without attempting the extremely difficult task of reconstructing three-ossicle middle ears, as Mills[1] advocates, the result of which would certainly be no better than a properly-constructed columellar prosthesis. In the many cases where incus and malleus can be preserved, however, Mill's suggestion of creating a small columellar replacement for the stapes alone, and thus maintaining a three-ossicle middle ear is very reasonable, provided that the lever arms of the malleus and incus have their normal configuration. As outlined above, the reconstruction of an effective lever ratio should always be given the highest priority.

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