Modeling Scala Media as a Pressure Vessel

Eric LePage and Åke Olofsson

Citation: AIP Conference Proceedings **1403**, 212 (2011); doi: 10.1063/1.3658088
View online: http://dx.doi.org/10.1063/1.3658088
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1403?ver=pdfcov
Published by the AIP Publishing

Modeling Scala Media as a Pressure Vessel

Eric LePage* and Åke Olofsson†

*OAEricle Australia, Perth, Australia
†Karolinska Institutet, Stockholm, Sweden

Abstract. The clinical condition known as endolymphatic hydrops is the swelling of scala media and may result in loss in hearing sensitivity consistent with other forms of low-frequency biasing. Because outer hair cells (OHCs) are displacement-sensitive and hearing levels tend to be preserved despite large changes in blood pressure and CSF pressure, it seems unlikely that the OHC respond passively to changes in static pressures in the chambers. This suggests the operation of a major feedback control loop which jointly regulates homeostasis and hearing sensitivity. Therefore the internal forces affecting the cochlear signal processing amplifier cannot be just motile responses. A complete account of the cochlear amplifier must include static pressures. To this end we have added a third, pressure vessel to our 1-D 140-segment, wave-digital filter active model of cochlear mechanics, incorporating the usual nonlinear forward transduction. In each segment the instantaneous pressure is the sum of acoustic pressure and global static pressure. The object of the model is to maintain stable OHC operating point despite any global rise in pressure in the third chamber. Such accumulated pressure is allowed to dissipate exponentially. In this first 3-chamber implementation we explore the possibility that acoustic pressures are rectified. The behavior of the model is critically dependent upon scaling factors and time-constants, yet by initial assumption, the pressure tends to accumulate in proportion to sound level. We further explore setting of the control parameters so that the accumulated pressure either stays within limits or may rise without bound.

Keywords: scala media, hydrops, pressure vessel, osmotic, aquaporin
PACS: 43.64.Bt, 43.64.Dw, 43.64.Gz, 43.64.Kc, 43.64.Ld, 43.64.Nf

INTRODUCTION

To model the mammalian cochlea, an early simplifying, but later crippling assumption may be the two-chamber model (2ChM). In it, the role of the helicotrema is assigned to equalising static pressures across the membrane separating the chambers. This has had the effect of focusing modelers' attention away from static pressures in the real chambers, particularly from the scala media (SM). In the absence of the need to consider pressures the field defaulted to consider how to counteract fluid damping. This switch of attention was certainly fateful considering that there is virtually no chamber nor vessel in the human body, however large or small, which does not attach high functional significance to static pressure. Any pressure rise in SM must potentially affect the stiffness of the cochlear partition, the place coding of frequency, the amplitude of motion and the OP of the OHC. In response to the confusing data and complex theories for compressive tuning, investigators have exacerbated the difficulty by being highly selective of data which only supported the 2ChM [1, 13].

It is well accepted that this tiny chamber (endolymph volume of a few microlitres) exhibits a significant hydromechanical phenomenon of its own—an increase in volume called *endolymphatic hydrops* (EH). Since it has only ever presented in pathological

What Fire is in Mine Ears: Progress in Auditory Biomechanics
AIP Conf. Proc. 1403, 212-217 (2011); doi: 10.1063/1.3658088

context for a half century it been regarded as abnormal and irrelevant to tuning.

The endolymph chamber is defined by three surfaces—the stria vascularis (which is essentially fixed in position), the basilar membrane (BM) and Reissner's membrane (RM) which are free to move. The passive stiffness of the BM is well studied and accepted as place dependent. RM appears planar and elastic in cross-sectional morphology from neonates, whereas it is often shown as flaccid in post-mortem histology from Ménière's patients, suggestive of its having been stretched beyond its elastic limit [3]. Uncontrolled static pressure rise is accepted as the cause of occasional ruptures of RM. In turn such ruptures offer the best explanation for Ménière's attacks [17], occasioning episodes of vertigo, due to propagation of pressure transients throughout the labyrinth. The preclinical phase for Ménière's disease (EH only) may last for years and never proceed to Ménière's disease [10]. Moreover, there is direct mechanical evidence suggesting such a pressure rise exists in animal models (e.g. [2, 15]).

The central question being addressed here is whether EH may represent a normal regulatory or homeostatic process whose stability is lost under certain conditions. If so, what mechanism could produce such volume variation and what purpose would it serve? It is significant that the osmolality of endolymph is higher than perilymph and decreases systematically from the base to the apex [16]. This suggests that any osmotic pressure gradient may not only be place-dependent but highly regulated. More recently, *aquaporins*, have been attracting intense interest throughout biology and not the least in studies of cochlear homeostasis (e.g. [7]). These are specialised water channels of 13 different types, of which aquaporins AQP4 and AQP5 are prominently represented in the membranes bounding the endolymph [6]. The simple fact that all cells in these membranes are also joined by tight junctions defines a pressure vessel. Aquaporins have remarkable properties facilitating *fast* water movement subject to an osmotic gradient.

The magnitude of osmotic pressure can be very significant relative to acoustic pressures (potentially high gain at dc). Moreover, the tiny volume could then exhibit a high *fractional volume change* (still more gain at dc). A rise in SM pressure would displace the BM towards scala tympani (ST) and RM towards scala vestibuli (SV). Since the OHC transduce displacement any static pressure variation cannot be incidental to OHC transduction (both forward and reverse) and the holistic function of the mammalian cochlea.

THE MODEL

For SM to function as a pressure vessel we begin by assuming that Reissner's membrane has finite stiffness at least comparable with that of the BM at the apex. The objective is control of the net stiffness of the cochlear partition. We postulate that we have two opposing processes, each of which has a different frequency and level dependence [9]. The distension of SM by water movement increases global stiffness, while over a local region defined by a pure tone stimulus, this change is opposed by OHC somatic motility.

1-dimensional passive delay line. For a first pass we use a conventional model to establish tonotopicity. We use a time-domain model using the Fettweiss wave digital filter approach first applied to the cochlea by Olofsson [11]. Now using MATLAB and SI units, we define 140 discrete segments to span the length of the mammalian cochlea.

For each segment, the parallel mass, compliance and viscous damping parameter values, as well as the mass coupling between the segments, are uniformly tapered such that the model exhibits a dispersive travelling wave with a place-frequency dependence following the Greenwood relation for the human case. The readouts from the model include all the local segment values of pressure, partition stiffness, displacement, velocity, depolarisation, plus the global pressure value. The first call initialises all the fixed parameters. All sections of the model are recomputed using a mex file for every time step of the stimulus. The model is run in callback mode such that many of the input parameters and signal characteristics can be varied from key strokes and the behavior observed directly. The display immediacy depends on processor speed.

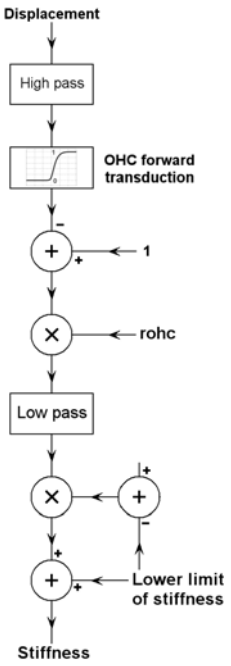

FIGURE 1. OHC axial stiffness; rohc is a scaling factor influencing the strength of somatic motility.

Role of OHC activity. Negative damping is considered a legacy of the 2ChM and is not required here. Of more immediate value to this model is the excitation-dependent axial-stiffness of the OHC [5]. As we will see, the stiffness of the cochlear partition depends jointly on the global pressure and on the stiffness of the OHC. The OHC serves two functions: (1) to locally modulate the stiffness of the cochlear partition and (2) to regulate homeostasis. The limits to which it can achieve both is set by the limits to which the somatic motility can be used to stabilize OHC OP through mechanical feedback—despite large variations in distension of the vessel. Thus the major component of stiffness is due to the tension generated in the organ of Corti by the static pressure. Accordingly, the stimulus generated potentials locally change that stiffness. In this implementation the local vibratory peak for a pure tone reduces the stiffness in proportion to their depolarisation which is computed from the forward transduction Boltzmann characteristic (parameters from [12]), see Fig. 1. Thus the lumped stiffness of the cochlear partition is reduced over a region which is spatially defined by the stimulus.

The novel feature—an accumulator. We incorporate a pressure vessel into the model such that any static pressure in the vessel containing incompressible fluid is uniformly distributed over all segments. Its operation is best described as a "sample-and-hold" of the acoustic pressure. The total pressure in any segment is the sum of the global pressure (sum of the partial pressures of all the segments) plus the local incremental pressure due to the stimulus. In every segment, if the total instantaneous pressure rises above the global pressure, the global pressure is increased. The rectifier efficiency is chosen to be low. The stiffness of the partition is related to the global pressure via a power law. The resulting displacement shifts the local OHC OP eliciting a contraction or elongation which changes the local stiffness of the cochlear partition in turn moving to reduce the error in the OP. There are five time constants considered: adaptation of forward transduction and charging and release time constants controlling the reverse transduction. The bulk flow of water molecules is not modeled specifically other than the action simulated via charge and release time constants governing global pressure.

RESULTS

The decline in lumped relative stiffness of the cochlear partition mimics the travelling wave envelope. The relation between relative stiffness and sound level has been chosen in the peak region (not shown) to exhibit virtually no change up to 70 dB SPL. Only with higher sound levels does the cell show sustained depolarisation accompanied by global OHC stereocilia displacements of micrometers. During this process the somatic motility is fedback so that the forward transduction maintains small-signal conditions. The panels in Fig. 2 are updated every 8 ms. They show the time course of the response of the model to the sinusoidal stimulus.

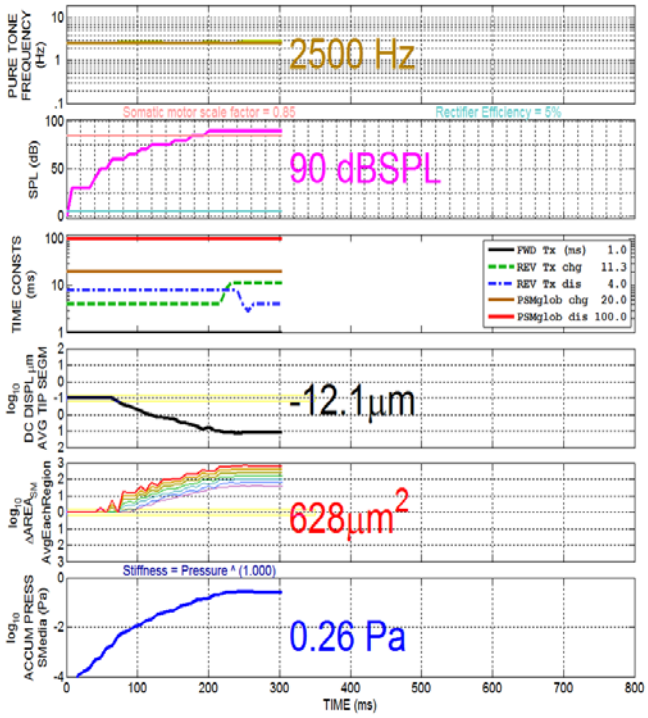

FIGURE 2. History of real-time driven experiment. A 2.5 kHz sinusoid is changed in level with resulting changes in BM displacement towards ST, volume increase at 7 places along length, and rise in global pressure in SM which lasts beyond when the level drops

As is seen in the top two panels, the frequency is fixed at 2.5 kHz, while the sound level is stepped as shown. The third panel shows the current values of the five time constants (ms). The fourth panel depicts the dc-displacement of the cochlear partition (up SV, down ST), the volume increase in seven equally-spaced cross-sections, and the rise in the global pressure in SM (Pa). Note that the ordinates are in log decades; the case of dc displacement zero represents 1 μm.

As will be demonstrated, the stability of the feedback is strongly dependent on the parameter values chosen and particularly upon the time-constants which control the motor response. Widely fluctuating slow pressure variations or escalating endolymph pressure occurs. The rate of decay of the global pressure towards that set by ambient noise level depends upon the time-constant controlling the rate of leak.

DISCUSSION

This work should be regarded as merely a first attempt to explore the signal processing possibilities of scala media being a pressure vessel. So far the utility of SM pressure is far from clear. It may serve only for high sound level protection. Conversely, the model demonstrates the possibility that the OHC may be not so much amplifiers as regulators of partition stiffness, predictably setting the OP of the inner hair cells at the same time.

Aquaporins and Osmosis. The weight of evidence now supporting fast osmotically-driven water transport in the cochlea cannot be ignored, nor its potential role as an internally-generated bias effect functioning as a modulator of stiffness of cochlear membranes. The factors controlling aquaporin gating of this water flux have yet to be determined, but a precedent does exist for aquaporins to be gated by pressure pulses.

Summating behaviors. We have explored how such behavior might be modeled—in a way which makes some sense of the different frequency and level dependences of the $-$SP and $+$SP [4]. We can now speculate that the weaker $-$SP may be due to somatic motility, while the stronger $+$SP is due to osmotic pressure. Thus, the energy in high level sound exposure is not dissipated as heat but is stored as potential energy.

Predominantly linear perception versus nonlinear behavior. This configuration describes an automatic gain control system (AGC) in which the global summating pressure in SM is the dominant control variable. The OHC somatic motility is "redeployed" to provide negative mechanical feedback to stabilize the forward transduction. In this *distension-tracking* function, as long as the OHC motility can restore the OP to the OHC's active region, the percept will be normal hearing, no matter whether the vessel is partly swollen or not. It is important to register that the model identifies SM pressure as a *hidden variable*, i.e. most physiologic and audiometric measures will betray little indication of its existence. Exceptions may be adaptive behavior and loud-sound-produced fatigue. Since water movement is postulated as the cause of SM swelling, the timing of this behavior may be strongly affected by factors other than the immediate sound history.

Endolymphatic hydrops and Ménière's disease. The model suggests that EH may represent a normal phenomenon marked by accumulation and release of endolymph volume and/or pressure. The model has much scope for demonstrating loss of homeostasis. Manipulation of reverse transduction timing can lead to unrestrained rise in pressure.

Legacy of two-chamber model and the apparent need for a cochlear amplifier. This model gives one important clue as to why the experimental evidence supporting negative damping is weak. At high frequencies an actual BM resonance above the noise level has never actually been seen in mammals. The central issue is the nature of the 1/f-type noise which is "obscuring" the presumed sinusoidal response to the stimulus. The recent trend has been to search for vanishingly small vibrations of cochlear structures using extraordinarily sensitive equipment. Such experiments have encountered unexplained instabilities [1]. Our model suggests that the problem is the methods used to "clean up" the signal. Narrowband filtering or extensive signal averaging is used, and typically this is time-locked to the pure tone stimulus [13, 14]. Even if the real movement responsible for the tip segment of the tuning curve is purely a drift (e.g. due to localised water movement), the product of the averaging must be a periodic waveform. So baseline shifts can appear to have magnitude and phase and masquerade as a cycle-by-cycle active process. The cochlear amplifier hypothesis rests entirely upon the presumption of linearity at low levels, viz. the active response has the same frequency as the stimulus.

Review of evidence of BM dc-shifts. In the light of the behavior of our model the dc-displacement results of BM measurements [8] are rendered considerably more plausible than they may have appeared at the time of publication. These probes had several operational advantages. Their rejection in favour of interferometers has implicitly assumed

that the methods of fringe-counting and phase unwrapping can cope with any slew rate. The signal from the fiber optic probe [9] was not averaged at all—it was amplified by a stable dc-offset amplifier and sent directly to a chart recorder. Somatic motility was then the only explanation for such "large" displacements. Other behaviors then reported [9] support this new class of model which achieves nonlinear compression simply by re-using the most common force in the body, osmosis, to set stiffness by the sound level.

ACKNOWLEDGMENTS

We are greatly indebted to our colleagues and families for continuing to support us in this work. ELeP also thanks the Université D'Auvergne and support from the Avan family.

REFERENCES

[1] Cooper NP, Rhode WS (1992) Basilar membrane mechanics in the hook region of cat and guinea-pig cochleae: Sharp tuning and nonlinearity in the absence of baseline position shifts. Hear Res 63:163–90

[2] Flock A, Flock B (2000) Hydrops in the cochlea can be induced by sound as well as by static pressure. Hear Res 150:175–88

[3] Hallpike CS, Cairns H (1938) Observations on the Pathology of Ménière's Syndrome. Proc R Soc Med 31:1317–1336

[4] Harvey D, Steel KP (1992) The development and interpretation of the summating potential response. Hear Res 61:137–46.

[5] He DZ, Dallos P (1999) Somatic stiffness of cochlear outer hair cells is voltage–dependent. Proc Natl Acad Sci USA 96:8223–8228

[6] Hirt B, Penkova ZH, Eckhard A, Liu W, Rask-Andersen H, Muller M, Lowenheim H (2009) The subcellular distribution of aquaporin 5 in the cochlea reveals a water shunt at the perilymph-endolymph barrier. Neurosci 168:957–970

[7] Huang D, Chen P, Chen S, Nagura M, Lim DJ, Lin X (2002) Expression patterns of aquaporins in the inner ear: Evidence for concerted actions of multiple types of aquaporins to facilitate water transport in the cochlea. Hear Res 165:85–95

[8] LePage EL (1987) Frequency-dependent self-induced bias of the basilar membrane and its potential for controlling sensitivity and tuning in the mammalian cochlea. J Acoust Soc Am 82:139–154

[9] LePage EL (1989) Functional role of the olivocochlear bundle: A motor unit control system in the mammalian cochlea. Hear Res 38: 177–198.

[10] Merchant SN, Adams JC, Nadol JB (2005) Pathophysiology of Ménière's syndrome: Are symptoms caused by endolymphatic hydrops? Otol Neurotol 26:74–81

[11] Olofsson Å (1983) Distortion measure based on a model for the auditory periphery. 11th International Congress of Acoustics. Thieme, Paris.

[12] Preyer S, Gummer AW (1996) Nonlinearity of mechanoelectrical transduction of outer hair cells as the source of nonlinear basilar-membrane motion and loudness recruitment. Audiol Neurootol 1:3–11

[13] Rhode WS (2007) Basilar membrane mechanics in the 6–9 kHz region of sensitive chinchilla cochleae. J Acoust Soc Am 121:2792–2804

[14] Sellick PM, Patuzzi R, Johnstone BM (1982) Measurement of basilar membrane motion in the guinea pig using the Mössbauer technique. J Acoust Soc Am 72:131–141

[15] Sirjani DB, Salt AN, Gill RM, Hale SA (2004) The influence of transducer operating point on distortion generation in the cochlea. J Acoust Soc Am 115:1219–1229

[16] Sterkers O, Ferrary E, Amiel C (1984) Inter- and intracompartmental osmotic gradients within the rat cochlea. Am J Physiol 247:F602–606

[17] Valk WL, Wit HP, Albers FW (2006) Rupture of Reissner's membrane during acute endolymphatic hydrops in the guinea pig: A model for Ménière's disease? Acta Otolaryngol 126:1030–1035