A Model of Viscoelastoplasticity in the Cochleo-Saccular Membranes

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**Introduction**: Variations in the distensile behavior of the cochleo-saccular vestibular membranes may contribute to lesion evolution of endolymphatic hydrops in Meniere’s disease. Such variation may be mediated through membrane viscoelastoplasticity. This feature may provide insight into the distensible process at work in these membranes.

**Hypothesis**: A precipitated collagen matrix can provide a suitable in vitro model of viscoelastoplasticity in cochleo-saccular vestibular membranes.

**Methods**: An in vitro extra-cellular matrix of precipitated collagen was evaluated as a model of suspected viscoelastoplastic behavior in the cochleo-saccular vestibular membranes. The structure of the precipitated collagen was assessed for its similarity to that of the basal lamina of the pars inferior vestibular membranes. The biomechanics of this matrix were scrutinized for evidence of viscoelastoplastic distensile properties.

**Results**: A matrix of precipitated collagen was found to exhibit a mesh-like fibrous structure similar to that of collagen found in the basilar lamina of the cochleo-saccular vestibular membranes. This matrix was also found to exhibit a sigmoid distensile response as well as strain rate sensitivity, both of which are characteristic properties of polymer viscoelastoplasticity.

**Conclusions**: An in vitro matrix of precipitated collagen appears to provide a suitable model that can account for variations in the distensile behavior of the cochleo-saccular vestibular membranes. The model exhibits viscoelastoplasticity and may have heuristic value in the analysis of lesion evolution in Meniere’s disease.

**Key Words**: Viscoelastoplasticity, cochlea, Reissner’s membrane, Meniere’s disease.

**Level of Evidence**: 6

**INTRODUCTION**

Reissner’s membrane normally has a linear configuration extending from the top of the spiral limbus to the superior margin of the stria vascularis in the cochlea. Endolymphatic hydrops is characterized by a variable degree of displacement of Reissner’s from this normal position into the scala vestibuli as shown in Figure 1. Minor fluctuations in the displacement of Reissner's membrane are thought to be physiological. Retrograde waves associated with otoacoustic emissions may be a manifestation of such normal functioning. The biomechanics underlying the transition from reversible physiological displacement to irreversible pathological deformity are not clear. A proposed double hit mechanism in the formation of endolymphatic hydrops in the cochlea-saccular membranes identified endolymphatic pressure and membrane elasticity as the potential determinants.\(^1\) Endolymphatic pressure variations may derive from alterations in secretion, osmosis, and resorption. How membrane elasticity might vary is less clear. This latter process may involve membrane viscoelastoplasticity. An in vitro model of the cochlea-saccular vestibular membranes that exhibits viscoelastoplastic behavior may provide insight into the in vivo distensile biomechanics of these membranes.

**METHODS**

An in vitro extra-cellular matrix of precipitated collagen was evaluated as a possible model of the cochleo-saccular vestibular membranes.\(^2\) The physical structure of the precipitate was compared to the known structure of the basal lamina of the vestibular membranes in the cochlea and saccule. The biomechanics of this matrix model were evaluated from reported tensile test data and scrutinized for evidence of viscoelastoplastic behavior.

**RESULTS**

The physical structure of the proposed collagen precipitate model was found to be a random irregular matrix of fibers similar in appearance to that collagen in the basal lamina of the vestibular membranes of the cochlea and saccule. This is shown in Figure 2, which is reproduced with permission.\(^2\)

This precipitated collagen matrix was found to exhibit a sigmoid distensile response characteristic of molecular polymers. This response consisted of an initial “toe” region of increasing stiffness, followed by a linear transition region, and then a terminal “heel” region of decreasing stiffness and impending rupture. This is illustrated in Figure 3, which is reproduced with permission.\(^2\)

The collagen matrix also exhibited strain rate sensitivity. Slowly applied strains were associated with less stress, greater membrane laxity, and greater distension...
before initiation of failure. Faster strains were associated with a more stiff response in the toe and linear regions and earlier onset of heel region failure. Such strain rate sensitivity is considered a characteristic of viscoelastoplastic behavior in polymers. These strain rate features are exemplified in Figure 4.

**DISCUSSION**

**Summary of the Results**

An in vitro precipitated collagen matrix has a tangled strand architecture that resembles that of the type IV collagen in the basal lamina of the pars inferior vestibular membranes. This matrix exhibits a sigmoid distensile response as well as strain rate sensitivity. Both features are characteristic of viscoelastoplastic behavior. These features appear to make such an in vitro matrix a suitable model of the in vivo distensile behavior of the cochlea-saccular vestibular membranes.

**Analysis of the Results**

Viscoelastoplasticity is a more elaborate response to stress than that of simple elasticity. Simple elasticity involves a time invariant linear response of the material. Simple elastic distention is near instantaneous and stress propagates through the material at the speed of sound. It is limited to that area of deformation where stress and strain are proportional in accordance with Hooke’s Law and is typically seen in solid materials with a crystalline lattice structure. Organic materials in contrast are often composed of long chain polymers that exhibit a more complex behavior known as viscoelastoplasticity. The
prefix “visco” implies that a viscous distention component may precede the elastic distention, while the suffix implies that a “plastic” distention component may succeed the elastic.

The origin of these observed material behaviors underlying the viscous, elastic, and plastic sectors of the collagen network stress-strain curve represents three different molecular aspects. The viscous portion is theorized to represent straightening of polymer chains in the mesh network. As distention begins the material acts in a viscous manner and becomes stiffer as polymer straightening approaches its asymptote. With further stress, distention is shifted to the covalent bonds holding the polymer molecules together as represented by the initial portion of the linear sector. At the inflection point where the slope of the linear sector starts to decrease, focal ruptures of the covalent bonds in some polymer molecules begin to occur and then accelerate as distention proceeds into the plastic sector. Fatigue effects due to cyclic loading of Reissner's membrane at low distention levels in the initial sector appear to be insignificant since Reissner's membrane can maintain its regular anatomical configuration for a lifetime in normal subjects. Fatigue may occur at points within the linear sector but is subject to repair as a living tissue if the applied pressure is moderate and transient. It will be associated with permanent plastic damage if the applied pressure is high and persistent.

Distention of such materials is usually strain rate sensitive, meaning that it takes more force to stretch the material quickly due to the presence of the viscous element. If force is applied gradually, significant distention occurs before the material shreds and ruptures. If force is applied abruptly, the viscous element will not have time to permit significant distension and if the applied force is sufficient, the elastic covalent bonds in the polymer backbone will rupture in a brittle manner akin to the manner in which glass breaks. These results shown here are consistent with these considerations and may offer an explanation of how the mesh-like structure of the model matrix induces its curvilinear distensile behavior and strain rate sensitivity. Low strain rates may permit the mesh to stretch and stiffen as the collagen fibers lengthen and change their alignment and thus exhibit an initial viscoelastic response with substantial distention before plastic failure. High strain rates may permit less time for fiber realignment and chain straightening that in turn lessen the viscous component of the response and result in early failure with limited matrix distention. Thus, high strain rates may cause matrix failure when the elastic limit is exceeded while low strain rates may cause matrix failure when the plastic limit is exceeded.

**Comparison of Results With Other Published Data**

The overall sigmoid shape of the collagen model matrix in vitro tensile response is consistent with the ex vivo distensile responses of porcine corneal strips. These exhibit an initial toe region of increasing stiffness, a subsequent zone of linear elasticity, and a terminal zone of plastic deformation and rupture. The overall similarity of these distensile responses of corneal collagen to those of the model matrix is clear and lends support to the validity of the collagen matrix as a model of viscoelastoplasticity.

The model matrix response characteristics are also consistent with the limited data available on the response characteristics of Reissner's membrane. When Reissner's membrane is subject to ex vivo tensile testing at a low distention rate of 0.58% per second, it exhibits a sigmoid response very similar in character to that of the model matrix, again consisting of an initial toe region of increasing stiffness, a subsequent zone of linear elasticity, and a terminal zone of plastic deformation and rupture. But when Reissner's membrane is tested at a rate of distention that is 10-fold higher at 5.6% per second, it exhibits a rigid response and brittle rupture in a manner consistent with abrupt elastic failure.

**Critical Analysis of Methods**

All science proceeds on the basis of models. In fact it has been wryly observed that “all models are wrong but some are useful.” For the current topic, the logistical and technical difficulties of procuring and tensile testing of fresh cochlea-saccular vestibular membrane are evidenced by the paucity of reported data in this domain. As a consequence, a model analog where the various parameters of stress strain and rate can be systematically assessed can provide additional insight into the biomechanical processes involved.

The in vitro precipitated collagen appears to be a good model of the cochlea-saccular vestibular membranes since both exhibit similar viscoelastoplastic behaviors. The in vitro tensile test characteristics of the model correlate very well with the ex vivo tensile test characteristics of human Reissner's membrane. This may reflect the fact that collagen type IV in the basement membrane is the main load bearing structure in the vestibular membrane. Any contribution by the epithelial and mesenchymal cells is thought to be minor since these cells separate during pronounced distention of these vestibular membranes while the basement membrane maintains its integrity in resisting the applied pressure.

Temperature has also been shown to exert an effect on distensile response and mode of rupture. Low temperatures are associated with minimal distention followed by an abrupt brittle type of rupture similar to that of glass. High temperatures are associated with marked distention followed by a stringy type of rupture like that of rubber. Intermediate temperatures are associated with moderate distention followed by a shredded type of rupture like leather. This leathery zone is where viscoelastoplastic behavior is manifest as shown in Figure 5.

This leathery viscoelastoplastic zone for collagen is around 35°C which approximates normal bodily temperature. Temperature variation effects are therefore not likely to play a role in tissue distensile responses in mammals when temperatures are maintained in the physiologic range.
Implications of the Results

The fact that extrinsic factors, such as strain rate and temperature, can influence the viscoelastoplastic behavior of collagen polymers, suggests that intrinsic factors may also exist. In fact, molecular structure has been shown to influence tissue distensile behavior. Human tendon has been shown to exhibit a very stiff response whereas raccoon skin demonstrates a very lax response based on the pattern of collagen molecular organization in these tissues. This raises the possibility that molecular structure of the collagen might be altered due to the influence of inflammation, toxins, vitamin deficiency, immunologic effects, viral infection, and so on. For example, structural defects are known to exist in mutant mice that lack nidogen which in turn leads to random ruptures in many of the basement membranes. These features have the implication that a combination of such extrinsic and intrinsic effects might make the basal lamina of the cochleo-saccular membranes more susceptible to endolymphatic hydrops.

CONCLUSIONS

An in vitro matrix of precipitated collagen can provide a reasonable model of the cochleo-saccular vestibular membranes. This model provides a better understanding of the process whereby variation in distensile behavior can occur due to membrane viscoelastoplasticity. This adds further evidence that a two hit mechanism may be operating in the formation of the membrane lesions seen in endolymphatic hydrops and Meniere’s disease.

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