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An Analogy between the Mucosal Waves of the Vocal Folds and Wind Waves on Water

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An analogy is made between the mucosal waves of the vocal folds, as represented by the two-mass model, and a model for the growth of wind waves on water. A layered-structure picture of the vocal folds helps in making the analogy, because this structure shares attributes of both situations. The simple analysis presented here suggests that the two-mass model may be modified to become a more histologically realistic, layered-structure model for mucosal wave dynamics.

INTRODUCTION

Waves, known as the mucosal waves of the vocal folds, can be observed on the surfaces of the vocal folds during phonation. This wave motion is a major part of the opening and closing of the vocal folds, particularly during the chest mode of phonation. The mucosal waves, observed under controlled conditions by Baer (Baer, 1975), can be seen under laryngoscopic examination. Wave fronts, or perturbations, on the surfaces of the folds move from the lower margins of the folds near the trachea to the upper margins of the folds near the vocal tract. The wave fronts extend along the length of each vocal fold from the posterior to the anterior portion of the fold.

One mechanical model of these waves is the two-mass model (Ishizaka & Flanagan, 1972; Ishizaka & Matsudaira, 1972) (see Figure 1). This model captures essential features of the air-solid interaction during phonation. (In this discussion and in the figures the air flow is horizontal along the x-direction, so the trachea is to the left and the vocal tract is to the right. The midline of the glottis is in the positive z-direction from one fold, and in the negative z-direction from the other fold.)

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The masses are sprung to an underlying substrate so that they can vibrate up and down in the z-direction. There is also a spring between the masses, the coupling spring, which tends to pull the masses so that they have the same z-coordinate. When the coupling spring between the masses is compliant enough, mass 2 lags mass 1 by as much as a quarter cycle during a simulation of chest mode phonation - mimicking the action of the mucosal wave. The wave travels from left to right, or from mass 1 to mass 2 , in the coordinate system of Figure 1.

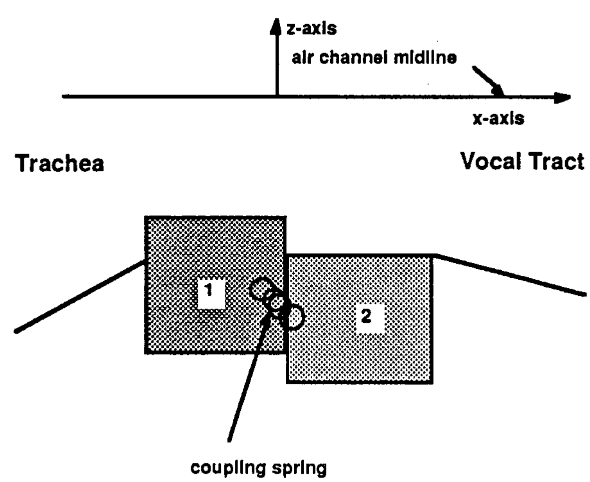

Figure 1.

An analogy to the the mucosal waves can be found in wind waves on water. The air motion along the water's surface can cause an instability, so that surface water wave motion ensues. Models have been invented to explain the initial stages of the growth of these waves from small perturbations. One of these models will be considered here in relation to the growth of the mucosal wave. To expedite the analogy between the two-mass model of the vocal folds and wind waves on water, the two-mass model is supplemented with a simplified layered-structure picture of the vocal folds, based on Hirano's studies (Hirano, 1981). The simplified layered-structure picture not only helps in the explanation of the mucosal waves, but it points to directions for future research in modeling the waves in a more realistic structure than provided by the two-mass model. While some of the underlying analysis used in this paper is mathematical in nature (Ishizaka & Matsudaira, 1972; McGowan, 1989), physical arguments can be used to convey the fundamentals of the analogy between the mucosal waves of the vocal folds and a model for wind waves on water.

WIND WAVES ON WATER

A consideration of other layered structures that show wave-like behavior when air passes over a surface is useful in understanding mucosal waves. One example is that of wind waves on water (Chandraesekhar, 1981; Lamb, 1945). This is a very simple layered structure consisting of two layers: air and water. Another, is structural instability resulting in vibration or flutter in the presence of air flow (Miles, 1956). Some common examples include a flag flapping in the breeze, or the destructive instability of aircraft panels that can occur during flight. In these examples there is the flow of air over a surface, which may or may not respond with wave motion or vibration, depending on its own mechanical properties, as well as those of the air. These are well studied areas in applied mechanics, and work in these areas can be studied for physical analogies. They all share the property that energy is transferred from the air to the surface to get wave action on the surface when the wind speed is great enough. Wind waves on water will be considered here because there is a model of wind wave growth on water that involves some of the same physics as that of the growth of the mucosal wave.

What is the instability that causes the growth of a wave from a small perturbation? When the water's elevation is perturbed above the flat, planar boundary by an amount ζ, there are the forces of gravity and surface tension to pull it back to the flat configuration (see Figure 2).

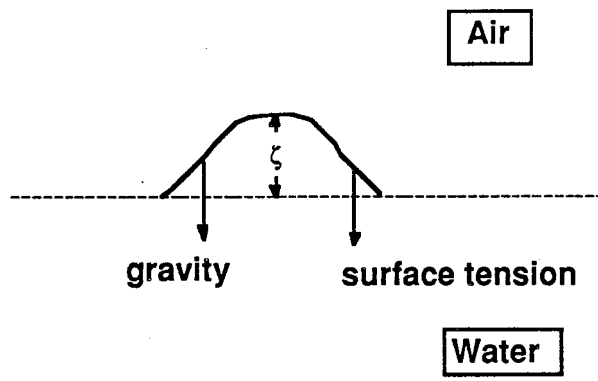

Figure 2.

It is assumed that there are always small perturbations to the base condition, so that there are spontaneous changes in the water's elevation. In equilibrium, with no perturbation, the air and water pressures are equal to P_0. If the pressures were not the same, there would be a net force at the surface of the water, and, hence, acceleration of the surface. But, when there is a perturbation to the surface elevation, the air pressure is perturbed by an amount p_a, and the water pressure by an amount p_w. These pressures in turn affect the surface elevation, ζ. Because elevation is a function of pressure, and pressure is a function of elevation, there is a feedback in the air-water system(see Figure 3). If, because of this feedback, the perturbation grows with respect to time, the configuration is said to be unstable and a wave may grow.

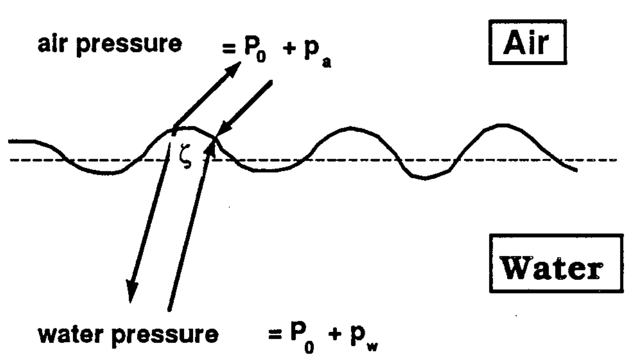

Figure 3.

To understand instability in this context, it is necessary to understand Bernoulli's relation, including the necessary conditions for its application. In the absence of friction and other energy loss mechanisms, in the absence of rotational motion of the air, and assuming the acceleration of the air can be neglected, the sum of pressure and kinetic pressure—total pressure—is constant. Kinetic pressure of air is the density of the air times the square of the air speed divided by two. Under these conditions of ideal flow, where Bernoulli's relation holds, the air moving at low speed is at a higher pressure than air at high speed: this is the Bernoulli effect. When a streamlined object is placed in a straight flow, the nose is under maximum pressure, because the flow is stagnant (see Figure 4). However, the pressure near the top of the object is slightly less than if there was no object in the flow. This is because the air accelerates over the top, giving a pressure drop by Bernoulli's relation (Lighthill, 1986). Given the necessary conditions for Bernoulli's relation in a region of flow, there is an inverse relation between pressure and flow speed.

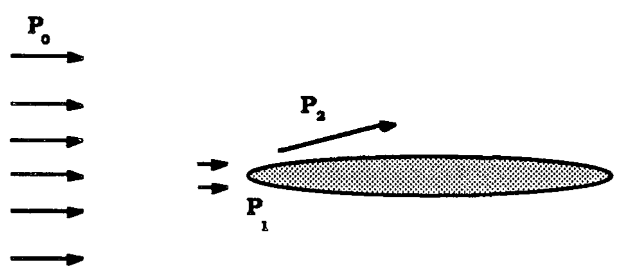

Figure 4. **Total pressure is equal everywhere, so that the air pressures are related $P_2 < P_0 < P_1$.**

At first the air flow resulting from the perturbations to the water's surface is assumed to follow Bernoulli's relation. That is, the perturbed water's surface is presumed streamlined and the flow of air ideal. (The quasi-steady approximation is used here, so the unsteadiness of the flow is neglected.) It can be seen that ideal flow is not the correct physical simplification in deriving the observed instability, and more realistic conditions must be incorporated to derive the instability.

To get a wave to grow with ideal flow conditions, it is necessary to counteract the restoring forces of gravity and surface tension. When the wind blows the air pressure decreases from what it was at rest as a result of the Bernoulli effect, and it is conceivable that the air pressure becomes so low so as to completely overcome the restoring forces (Miles, 1960). This is known as a static instability where, at least initially, the water is literally sucked into the air as if by a vacuum cleaner. Here there is an exponential growth in the elevation of the water. However, because the restoring forces of gravity and surface tension are so strong, the wind velocities required for this are much higher than those observed during wind wave production. (In the case of the flag, there is little restoring force perpendicular to the vertical plane, so this type of instability can get the flag to flap in the breeze.) Requiring that the restoring forces be overcome is too stringent. All that is needed is for energy to be fed from the air into the water at such a rate so as to overcome the any energy dissipation mechanisms. A negative resistance must be added to the system so that a different type of instability results: dynamic instability.

To derive a dynamic instability, the assumption of ideal flow of air must be abandoned. This can be seen by considering the following example. Suppose a sinusoidal perturbation is created on the surface of the water. If the air flow is symmetric over the maxima and minima, as it would be in the case of ideal flow, then both the air and water pressures are symmetric about the maxima and minima. This results in no net energy transfer from the air into the water, that is, there is no net power input from the air to the water. In the case of water-air surfaces, power input per unit area is calculated as the water pressure at the surface minus air pressure at the surface, which gives net pressure at the surface, times the vertical velocity of the surface. When the surface of the water is perturbed, there is vertical movement of the surface. Because of the symmetry of a sinusoidal perturbation, for each section going up with a given net pressure there is a section going down with the same speed and same net pressure, so that one product of net pressure difference times velocity will be the negative of the other. Therefore, there is no net power input from the air to the water. A feedback mechanism capable of breaking the symmetry provided by ideal flow is needed for a dynamic instability that can explain the formation of wind waves over water at a relatively low wind speed.

It is instructive to consider the first model of dynamic instability for wind waves on water. Despite the fact that it is not the correct model for the growth of wind waves on water (Miles, 1957; Lighthill, 1968), this model provides an analogy for the mucosal wave. Jeffreys (Jeffreys, 1925) proposed that the symmetry in air pressure between the windward and leeward side of a maximum is broken because of the phenomenon of flow separation. That is, vorticity is shed from the wave crests, which means that ideal flow no longer exists in all regions of the air flow, because the presence of vorticity means that rotational fluid motion is present. This symmetry breaking mechanism is known as Jeffreys' sheltering hypothesis. This is, for example, what happens to a blunt object, like a house, in wind, where vorticity is shed from the roof (see Figure 5). Because energy is transferred into the vorticity, the total pressure on the windward side of the house is greater than that on the leeward side, and the stronger the vorticity the greater the difference in total pressure. Further, because the air speed is zero along all surfaces of the house, the air pressure on the windward side is greater than that on the leeward side.

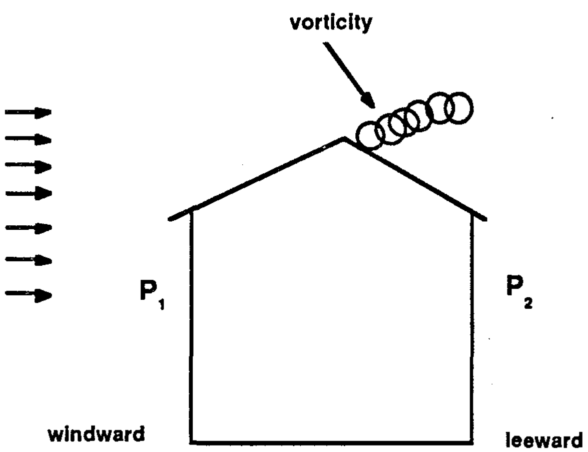

Figure 5. **Total pressure on the windward side > total pressure on the leeward side, so that the air pressures are related $P_1 > P_2$.**

With the abandonment of ideal flow in the case of the air-water interface, there is a difference in the total pressure on the windward side and the leeward side of a crest. For water waves traveling in the same direction as the wind, the sides moving downward are also windward and, hence, under greater air pressure than the leeward sides which are moving upward. This means that more energy is fed into the water in the downward motion than is taken away in the upward motion. The net energy transfer is into the water, if the initial sinusoidal perturbation represents a wave traveling in the same direction as the wind. Wave growth ensues if the energy gained in a cycle is greater than that lost by dissipation mechanisms. This is a dynamic instability, where there is exponential growth of oscillation rather than the pure exponential growth seen for static instability.

The relevance of the above considerations to the two-mass model of the vocal folds is that there is vorticity formation at the glottal entrance and exit. This allows energy to be fed from the air into the vocal folds in the event the surfaces of the folds at the glottal entrance and exit are out of phase. Before the details of the analogy are spelled out, the layered-structure picture of the model folds is described.

LAYERED STRUCTURE AND ITS RELATION TO THE TWO-MASS MODEL

To draw an analogy between Jeffreys' model for the growth of wind waves on water and the mucosal waves as described by the two-mass model, some of the essential histological features of the vocal folds are used to build the layered-structure picture of the vocal folds. In particular, the description of the layered structure of the folds near the edges as provided by Hirano (Hirano, 1981) is used (see Figure 6). Consider a single fold. The epithelium is in contact with the air, which is flowing in the x-direction. Below this (in the sense of away from the mid-line) is the superficial layer of the mucosa, otherwise known as Reinke's space. The intermediate and deep layers are ligamentous and muscular layers, and these are grouped together in the simple layered-structure picture presented here. Note that the two-dimensional aspect of the two-mass model is being followed in the layered-structure description of the folds, so variations in the anterior-posterior dimension are not allowed.

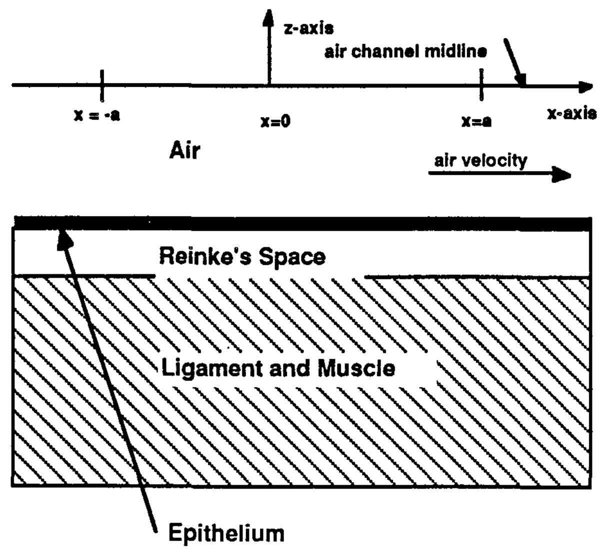

Figure 6.

The epithelium is a thin, elastic sheet. The epithelium is assumed to be relatively elastic because of the tight interconnections between the cells provided by the desmosomes (Junqueira, Carneiro, & Long, 1986). This elasticity provides a restoring force when the epithelium is stretched and perturbed similar to the way a drumhead behaves. It is important to note that the shorter the length scale, or wavelength of a perturbation, the stronger the restoring force. [This is only a linear analysis, the change in tension with amplitude of vibration is not be taken into account (Titze & Durham, 1987). Further, bending stiffness could be taken into account in a more detailed analysis (Bickley, 1987).]

In contrast with the epithelium, the material of Reinke's space behaves more like an inelastic fluid. Reinke's space is an amorphous suspension of collagenous fibers (Junqueira, Carneiro, & Long, 1986). The fact that these fibers are not connected together means that the elasticity of the fibers do not act to make Reinke's space elastic. The Reinke's space pressure will also be affected by the elevation of the epithelium.

Finally, the ligamentous and muscle layers constitute a single layer in this simplified picture. This layer reacts to perturbations and stresses from the other layers, and the reaction is parametrized as an impedance seen from Reinke's space. For a thin Reinke's space, the mass, stiffness, and damping add to corresponding quantities of the epithelium, so that changes in mechanical quantities in the underlying ligament-muscle layer have a direct effect on the mechanics of the epithelium.

The only changes from the two-mass model in adopting the layered structure picture are to replace the masses in the two-mass model with the layered structure, and to replace the springs, which provide the restoring forces in the two-mass model with the tension in the epithelium and the underlying ligament-muscle stiffness. The laws governing the air flow are left unaltered. The air flow obeys Bernoulli's relation, except at the entrance and exit of the glottis, where there can be change in the total pressure. The total pressure decreases from the tracheal region to the glottal region because of vorticity at the glottal entrance, and the total pressure decreases from the glottal region to the vocal tract because of vorticity formation at the glottal exit. However, Bernoulli's relation holds locally within the trachea, glottis, and vocal tract. Feedback exists here because the amount of vorticity depends on the the elevation of the epithelium within the glottal region and the amount of vorticity, in turn, determines the air pressure at the epithelial surface. This feedback can provide for an instability for wave growth on the epithelium.

INSTABILITY OF THE LAYERED STRUCTURE

With the layered-structure picture, the stability of the epithelial surface is analyzed in essentially the same way that Ishizaka and Matsudaira analyzed the stability of the two-mass model (Ishizaka & Matsudaira, 1972; McGowan, 1989). To study stability, it is necessary to consider what occurs with air flowing at velocity U and given that the epithelium has a perturbation elevation, ζ, when the equilibrium configuration is one with plane boundaries between the layers and no air flowing. In the perturbed state, both the air pressure and Reinke's space pressure are perturbed, as is the ligament-muscle layer. Because the pressures in each the air and Reinke's space depends on the elevation, ζ, there is feedback occurring. For instance, as the epithelium encroaches on the air channel in the form of a bump, there must be a slight increase in air speed over the bump. This, in turn, means a slight decrease in pressure by Bernoulli's relation, and this tends to make the bump grow in amplitude. If it were not for the combined restoring force of the elastic epithelium and the underlying ligament-muscle layer, this bump would just keep on growing.

It must be noted that the Bernoulli effect is amplified when the air is channeled as it is in the glottis. Not only is the air speed greater because of the constriction, but it can be shown mathematically (Ishizaka & Matsudaira, 1972; McGowan, 1989) that the boundary conditions provided by the channeling of the air greatly amplifies the importance of the air flow and, in particular, the Bernoulli effect. Because the Bernoulli effect acts against the restoring forces, the effective restoring force of the epithelium can be greatly reduced with increased air flow and the narrowing of the glottal channel. Note that it is the combined effects of the epithelial tension, underlying ligament-muscle stiffness, and the Bernoulli force that determines the total effective restoring force. It is not any one effect determining the vibratory characteristics of the folds in small amplitude vibration.

Because of the large Bernoulli effect, it is not surprising that static instability is possible for the epithelium. Recall that for wind waves on water that static instability results when the reduction of pressure due to the Bernoulli effect overcomes the restoring forces of gravity and surface tension. The conditions under which this would occur in the case of the vocal folds are a loose epithelium and loose vocalis, perhaps meaning a relaxed cricothyroid muscle, as well as closely approximated folds and a fairly healthy airflow, both to enhance the Bernoulli effect. It may be that the closing phase of creaky voice can be understood as having conditions near static instability for a good part of the closing phase.

However, this severe static instability cannot be relied on to produce the mucosal wave in chest voice. The Bernoulli effect may lessen the effective epithelial tension, but it does not overcome the restoring forces. As in the case of wind waves on water, vorticity must be brought into the picture. Ideal flow conditions giving Bernoulli's relation do not hold at the entrance and exit of the glottis because of the vorticity provides an additional feedback mechanism.

This feedback is a little more complex than Jeffreys' sheltering mechanism for wind waves on water because volume velocity, in addition to total pressure, is changing with the vorticity formation in the case of the vocal folds. Consider the glottis to extend from -a to a along the length of the of the epithelium in the x-direction. Figure 6 shows a schematic of the layered-structure picture of one of the folds with one-half the air channel. Mathematical analyses show that the feedback mechanism for the vocal folds only works on the part of the epithelium closest to the trachea, the lower margins, say, between -a and 0. ('Lower margins' in the coordinate system here are the parts of the folds furthest to the left.) The parts of the epithelium closest to the vocal tract, the upper margins, between 0 and a, are relatively unaffected by this mechanism. If the lower margins of the epithelium are moved toward the midline, the consequence of increased vorticity formation at the glottal entrance is an air pressure deficit at the lower margins. With increased vorticity formation at the glottal entrance comes a greater difference in total pressure between the trachea and the glottis, and, hence, a smaller total pressure for the glottal region. As long as the air speed is maintained sufficiently over the lower margins, this will mean a pressure drop in the air pressure over the lower margins. If the upper margins of the epithelium are raised, there is a pressure excess at the lower margins of the folds. With greater vorticity formation at the glottal exit comes a greater difference in total pressure between the glottal region and the vocal tract. This means that there is less difference in total pressure between the trachea and the glottis, because the difference in total pressure between the trachea and vocal tract is constant. So, there is an increase in total pressure in the glottal region with elevated upper margins. As long as air speed does not increase too much over the lower margins, there must be a pressure increase over the lower margins.

Given these facts, if the upper margins of the epithelium are somewhere around a quarter cycle behind the phase of the lower margins, then the following events occur during a cycle. While the lower margins of the epithelium are moving toward the midline, the upper margins are away from the midline, giving a pressure deficit on the lower margins. There is a pressure excess on the lower margins while the lower margins of the epithelium are moving from the midline because the upper margins are high. Therefore, this feedback is such that the pressure on the lower margins is greater during its downward motion than on its upward motion, and there is net power input from the air into the epithelium. If the power is great enough to overcome the rate of dissipation by damping, then surface waves grow (Stevens, 1977). This is the scenario for waves of wavelength of around 4a traveling in the direction of flow, because such waves provide the correct phasing between the upper and lower margins of the folds.

As in the case of Jeffreys' sheltering hypothesis, vorticity is used to break the symmetry in the pressures on the upstroke and downstroke of a surface. This is essentially a feedback mechanism, because the strength of the vorticity depends on the height of the surface.

CONSEQUENCES AND FUTURE RESEARCH

The analogy between explanations of wind waves on water and the mucosal waves of the vocal folds adds to the understanding of the physics of phonation. For instability to result, the energy input by a feedback mechanism must overcome any dissipation of energy. Energy dissipated in each cycle increases with frequency and, hence, restoring force. So, air flow helps to create the dynamic instability in two ways: It provides for vorticity formation and it reduces the effective restoring force of the folds through the Bernoulli effect in the glottal constriction, thus reducing the rate of dissipation.

There must be a phase difference between the upper and lower margins of the folds for the kind of instability described here to occur. This puts an upper limit on the wavelength of the mucosal wave, because for long wavelengths, the upper and lower parts are nearly in phase. However, there is one more necessary condition for this instability: The energy input by the special feedback mechanism must be greater than the energy lost by dissipation. Energy dissipation increases with decreasing wavelength. The two necessary conditions for dynamic instability have opposite wavelength dependence: phasing requiring shorter wavelengths and that of keeping dissipation bounded requiring longer wavelengths. Under certain conditions, such as a tense cricothyroid, these requirements may be incompatible, so that another type of instability must be sought to explain wave growth. The mode of vibration when the two conditions become incompatible is one-mass vibration seen in falsetto voice.

The use of a layered-structure picture of the vocal folds has expedited the analogy between the mucosal wave of the vocal folds and wind waves on water. It is hoped that the feasibility of a layered-structure approach to vocal-fold mechanics has been demonstrated in this paper. More explanation of the voice modes using this approach is not possible without some added, important factors, such as the third, anterior-posterior dimension and nonlinear interaction. Numerical computation will eventually be needed for further progress.

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