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The Miracle of Producing a Large Pitch Range

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IF THERE IS ANYTHING MIRACULOUS about the nature of human voice production, it is the ability to produce a pitch range of several octaves. Based on the physical make-up of the vocal instrument, one would never predict such a pitch range. Human tissue is highly energy absorbing, there is only one "string" to play, and the ability to change vocal fold length and tension is quite restricted. Nevertheless, nature has developed extraordinary ways of coping with these limitations.

Let me discuss the apparent limitations one at a time. Consider first the process of energy absorption. Because the vibrating portion of the vocal folds is filled with liquid-like material, and because the liquid is viscous (it resists being deformed rapidly as molecules slip and slide over each other), considerable vibrational energy is absorbed and converted to heat energy due to friction. If the liquid material were like oil or glycerin, its viscosity would remain relatively constant with changing frequency. Since it is known that the frictional energy loss is proportional to the square of the frequency for constant viscosity, the vocal folds would not be able to sustain their oscillation for more than a few notes on a musical scale. The energy derived from the glottal airstream would not be able to overcome the frictional energy loss. So, how is self-sustained oscillation achievable over several octaves? The answer lies in the fact that vocal fold tissues become less viscous with increasing frequency. In a systematic way, the molecular bonds between adjacent molecules become weaker and weaker, creating less friction at high rates of deformation.[1]

Consider now the mechanism for changing tension (or stiffness) of vocal fold tissues for the purpose of changing fundamental frequency. In most stringed instruments, there are pegs around which steel wire or gut can be wrapped to make a string stiffer. The human larynx has no such pegs. The only way to increase tension is to elongate the tissue, unless it has internal contractile properties like muscle. Much of the tissue in vibration is nonmuscular, however. The problem is that longer strings vibrate at lower frequencies, all else being equal. The tension has to increase dramatically, therefore, to overcome the drop in frequency due to greater length. A simple formal for the frequency of a vibrating string is

$$F_o = \frac{1}{2L} \sqrt{\frac{\text{stress}}{\text{density}}} ,$$

where L is the string length, *stress* is the tension in the string divided by its cross-sectional area, and *density* is a constant value (about 1.0 g/cm^3) for soft

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tissue. Because stress is under the square root, it requires a 4:1 increase in stress to overcome a 2:1 increase in length, just to keep the frequency constant. For a four octave frequency increase, F_0 increases 2x2x2x2 = 16 fold (every octave multiplies the frequency by two). If the length increases by a factor of two over these four octaves, then the stress in the tissue has to increase by a factor of $(2x16^2) = 1024$. This is an enormous requirement, to increase the stress in soft tissue by a factor of 1000 by simply doubling its length! How does nature do it?

There are two possibilities. We know that the vocal ligament is composed of densely packed collagen fibers that can support large tensions when elongated beyond about 30–50%. These tensions are distributed over a small cross-sectional area in the ligament (on the order of 1.0 mm^2), thereby causing stresses on the order of 1.0 MPa (mega-Pascals). This is compared to about 1.0 kPa (kilo-Pascals) for normal soft tissue without a large concentration of collagen fibers. Hence, the 1000:1 increase in stress can be explained by the presence of a vocal ligament in humans. (The pig also has a vocal ligament, which explains its ability to squeal at high pitches.)

In addition, the vocal ligament has developed a thickening at the end points known as the *macula flavae* (yellow spots) in anatomical terms. These thickenings prevent the ligament from "kinking" at the anterior and posterior cartilage attachments, making the effective length of the ligament in vibration shorter.[2] Thus the factor of two lowering of F_0 due to vocal fold elongation may actually be offset by these extra stiffnesses at the end points.

In summary, the development of vocal fold tissues to accommodate vibration over large pitch ranges is nothing short of a miracle. A fascinating experiment (which cannot be performed) would be to expose one vocal fold of a human being to normal daily vibration from birth to adulthood while preventing the other vocal fold from vibrating at all. We could then answer questions about whether such specialized tissue development is driven purely by the applied forces or partly by genetics. Perhaps a clever human or animal study is on the horizon that answers this question indirectly.

REFERENCES

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