Simulations of Vocal Fold Dynamics using MPMICE

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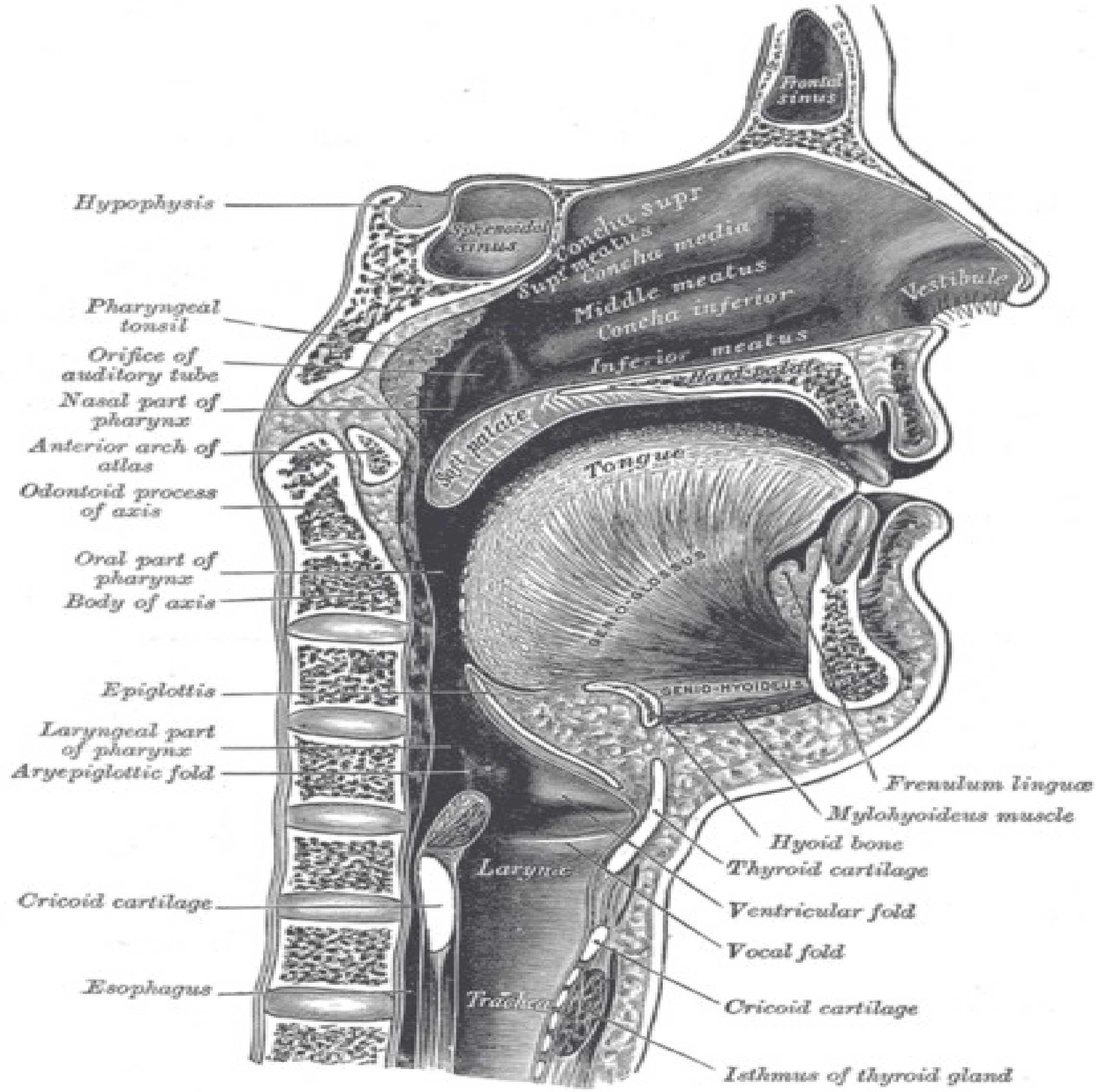
Outline

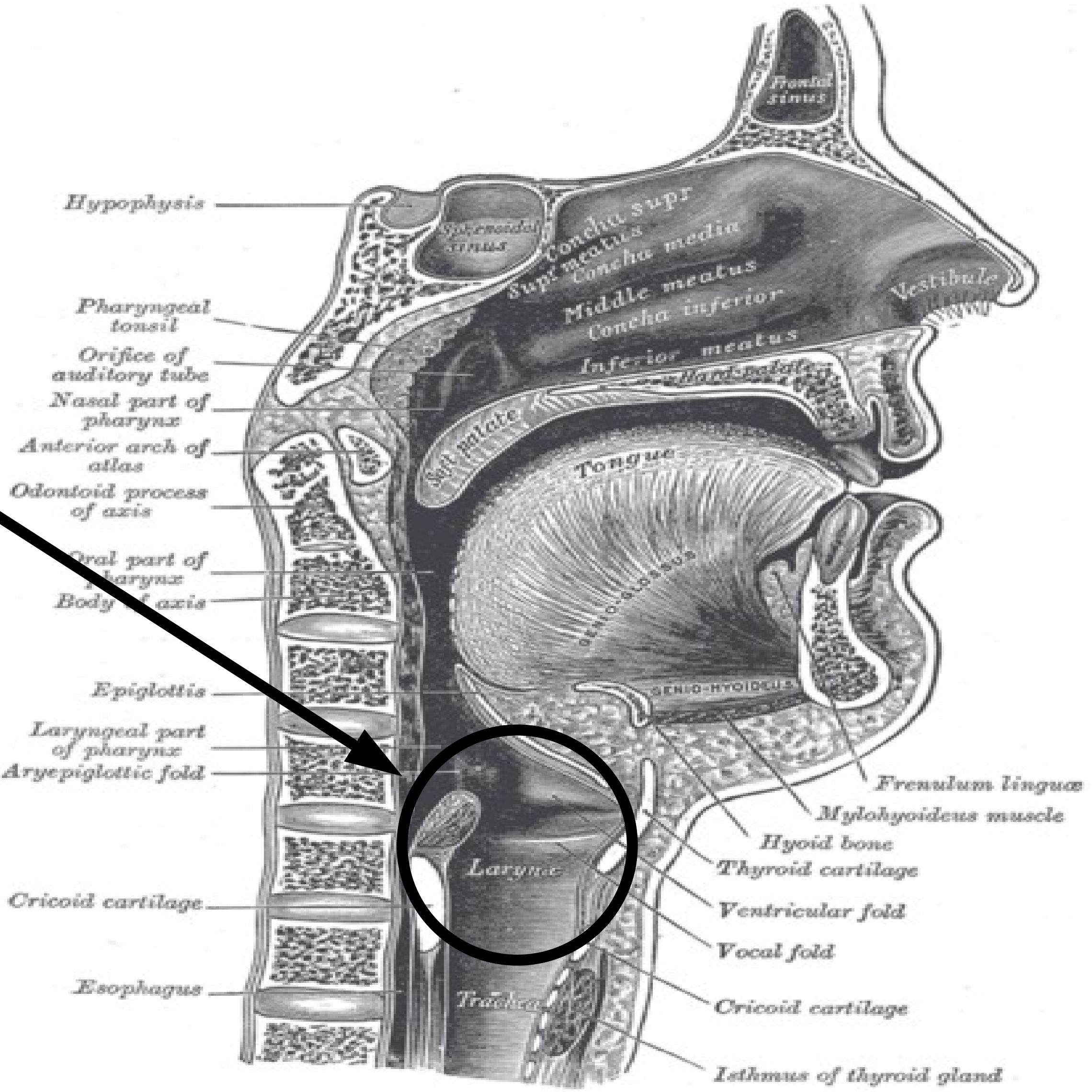
- Basics of the structure of the larynx and the mechanism for the production of sound
- Brief outline of MPMICE in relation to the vocal fold and aerodynamics problem
- Preliminary vocal fold material model
- Example simulations for $P_{subglottal} = P_{atm} + 800$ Pa
- Current developments

How does phonation occur?



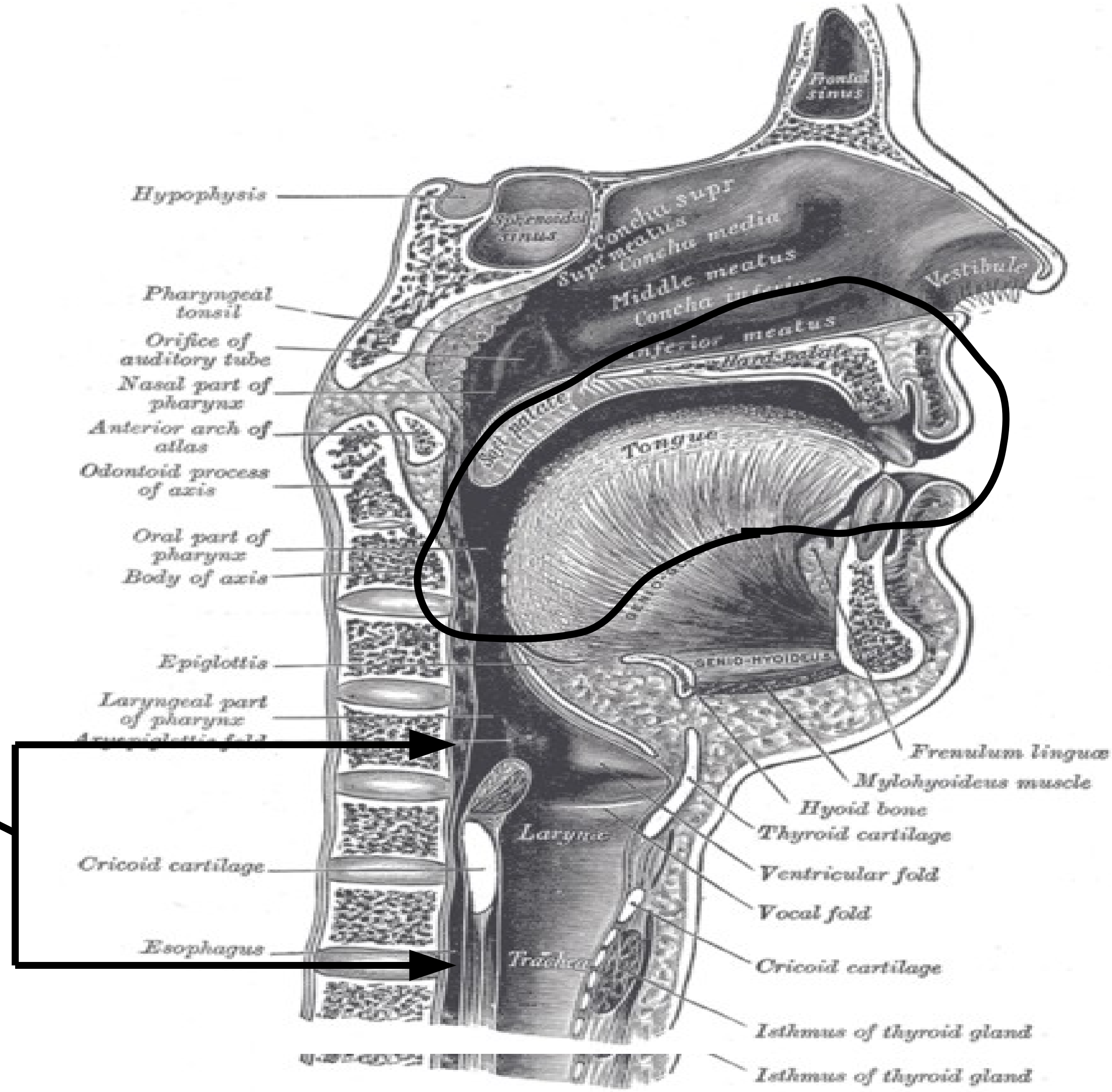
Phonation

- Occurs in the the larynx at the level of the vocal folds



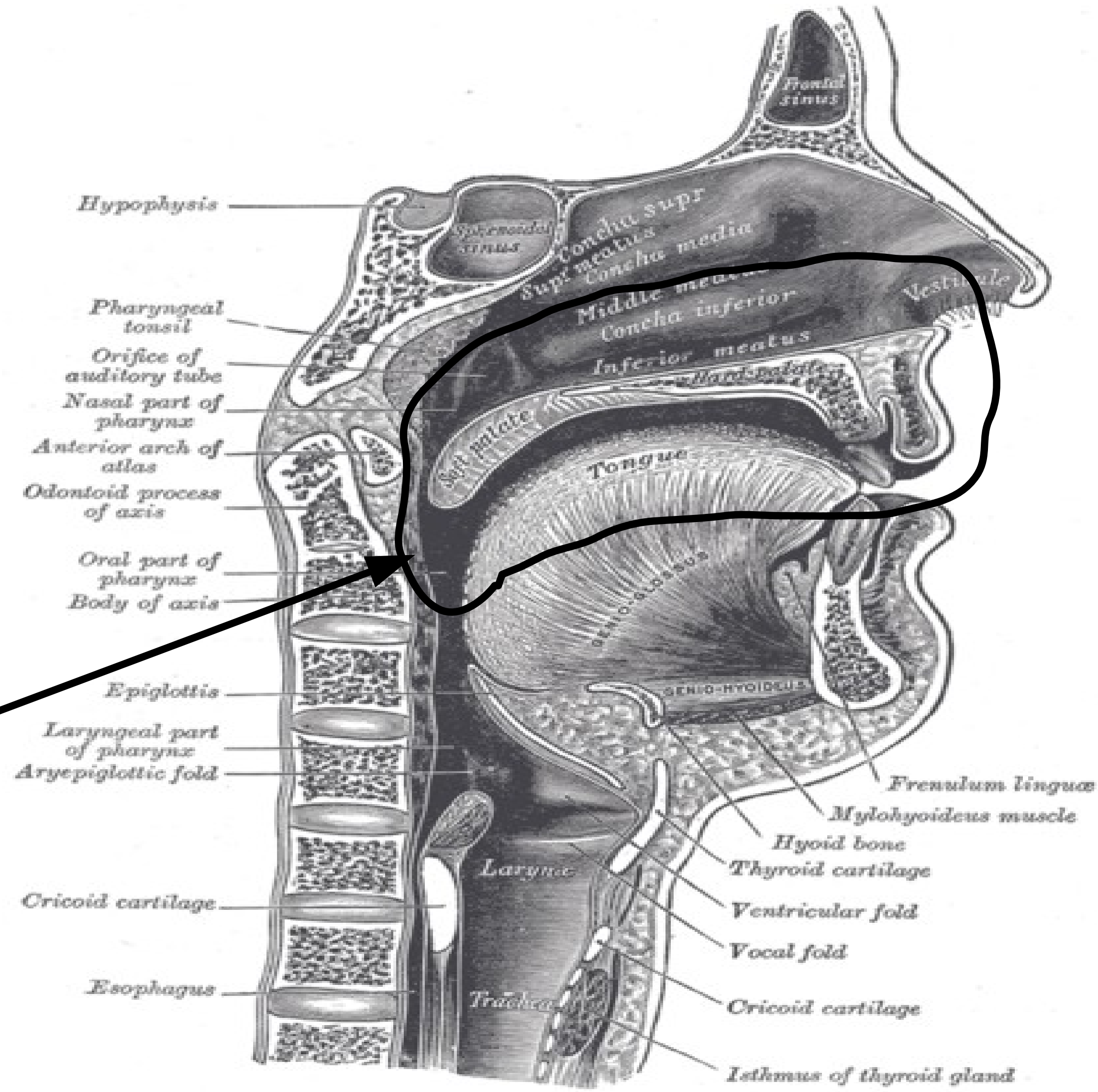
Phonation

- Occurs in the vocal folds in the larynx
- A stream of air with sufficient transglottal pressure induces the vocal folds to vibrate ~130 Hz for males & ~260 Hz for females



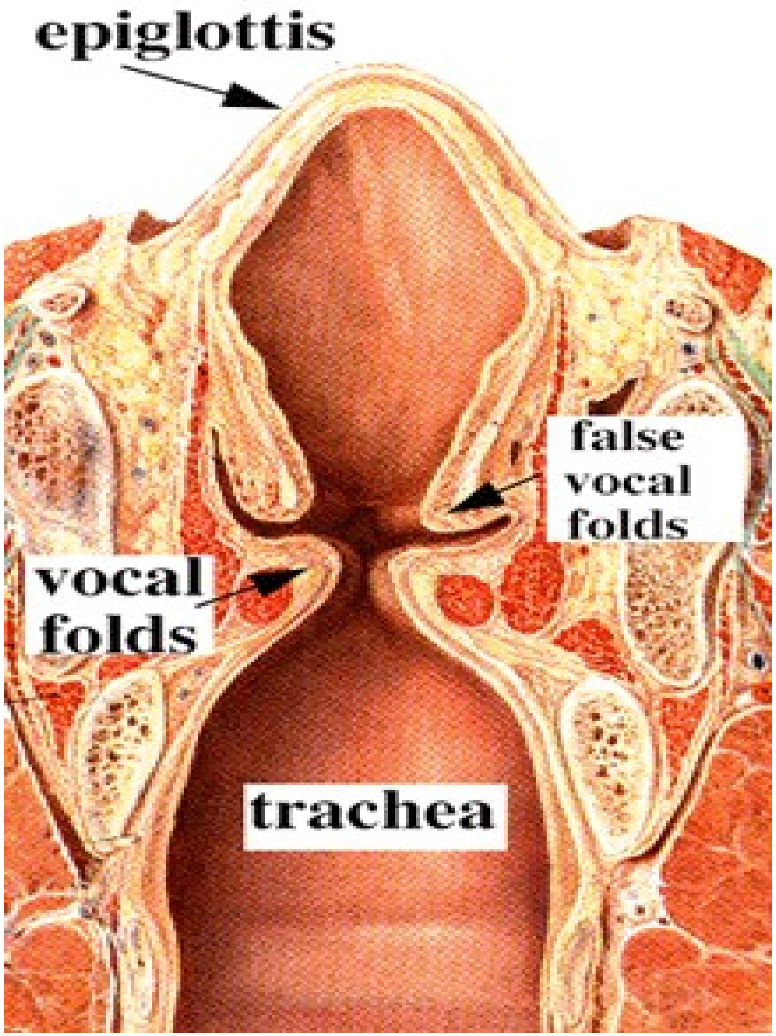
Phonation

- Occurs in the vocal folds in the larynx
- A stream of air with sufficient transglottal pressure induces the vocal folds to vibrate ~130 Hz for males & ~260 Hz for females
- Sound shaped by pharynx, nasal & oral cavities



Basic overview of vocal fold dynamics

- Lungs supply pressure of 1500 Pa above atmospheric pressure
- Air flows through glottis inducing vocal folds to separate via positive pressure
- Vocal fold material properties react to bring vf back toward initial state
- Result is a 'pulse' of air which flows toward mouth

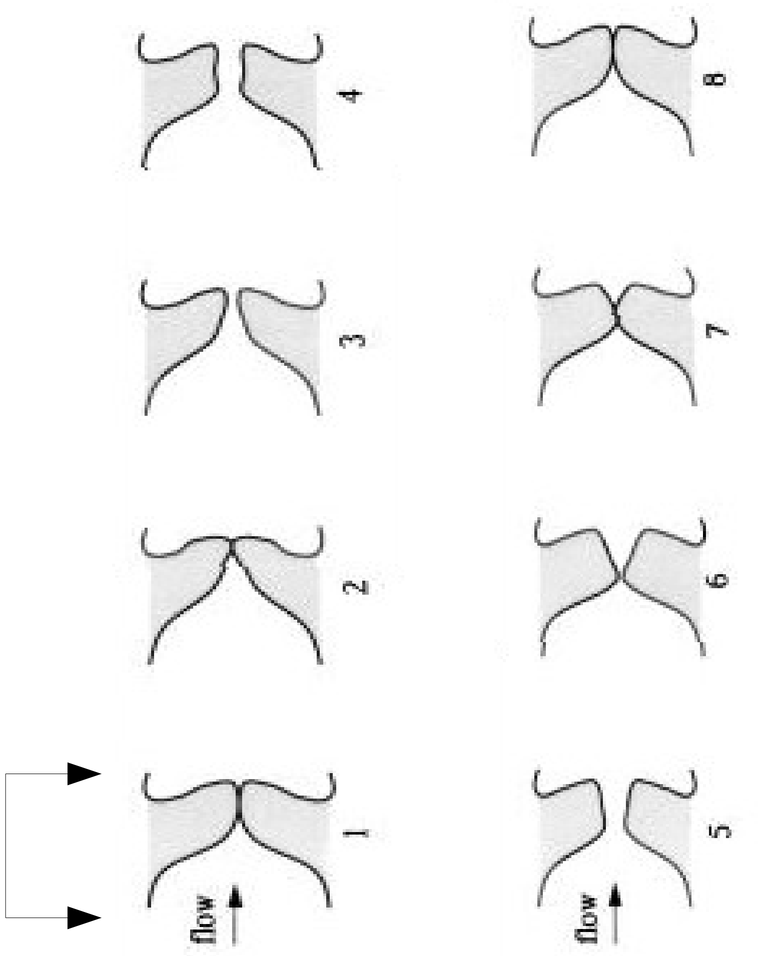


A Complete Vibration Cycle

- VF begin closed(1)
- Pressure gradient induces lower part to open first (2-4)
- VF material reacts back to closure (5-8)
- Note phased opening and closing

Coronal slice across vf

$$\Delta P \simeq 800\,Pa$$



Vocal Fold-Aerodynamics Modeling

- Air flow exerts force on the vocal folds (vf) which are displaced
- Material properties of vocal folds act back to restore the vf to their initial positions
- Both the air flow and the vf material dynamics are interdependent
- The physiological response is emergent
- The problem is thus a type of Fluid-Structure Interaction problem

Multifield Approach to FSI

- Averaged model which allows both air and vf to exist at any point of space with some probability-- developed by Bucky Kashiwa et al at LANL, uses MPM for material modeling -developed by Sulsky et al and ICE for air
- Strong interactions between the air and the vf materials (so N=2 here)
- Full Navier-Stokes for air and transient nonlinear response of the vocal fold material
- State vector for r-material $\langle M_r, \boldsymbol{u_r}, e_r, T_r, v_r, \theta_r, \boldsymbol{\sigma_r}, p \rangle$

State of each material

- M_r mass of r-material
- $\mathbf{u}_r$ velocity of r-material
- e_r internal energy per unit mass of r-material
- T_r temperature of r-material
- v_r volume per unit mass of r-material
- θ_r volume fraction of r-material
- $\boldsymbol{\sigma}_r$ Stress of r-material
- P equilibrium pressure

Basic Equations of Multifield Model of FSI

$$\frac{1}{V}\frac{D_r M_r}{Dt} = 0$$

Conservation of Mass

$$\frac{1}{V}\frac{D_r (M_r u_r)}{Dt} = \theta_r \nabla \cdot \boldsymbol{\sigma} + \nabla \cdot \theta_r (\boldsymbol{\sigma_r} - \boldsymbol{\sigma}) + \sum_{s=1}^{N} \boldsymbol{f_{rs}}$$

Conservation of Momentum

where

$$\boldsymbol{\sigma} = -p\boldsymbol{I}$$

mean stress

and

$$\boldsymbol{f_{rs}} = K_{rs}\theta_r\theta_s(\boldsymbol{u_r} - \boldsymbol{u_s})$$

momentum exchange force

$$\sum_{s=1}^{N} \theta_r = 1 \quad \Rightarrow \quad 0 = 1 - \sum_{s=1}^{N} \rho_r v_r$$

Solved to obtain equilibrium pressure

Basic Equations of Multifield Model of FSI (cont'd)

$$\frac{1}{V}\frac{D_r(M_r e_r)}{Dt} = -\rho_r p \frac{D_r v_r}{Dt} + \theta_r \boldsymbol{\tau_r} : \nabla \boldsymbol{u_r} - \nabla \cdot \boldsymbol{j_r} + \sum_{s=1}^{N} q_{rs}$$

Conservation of Energy

where $\boldsymbol{j_r} = -\rho_r b_r \nabla T_r$ Heat flux current

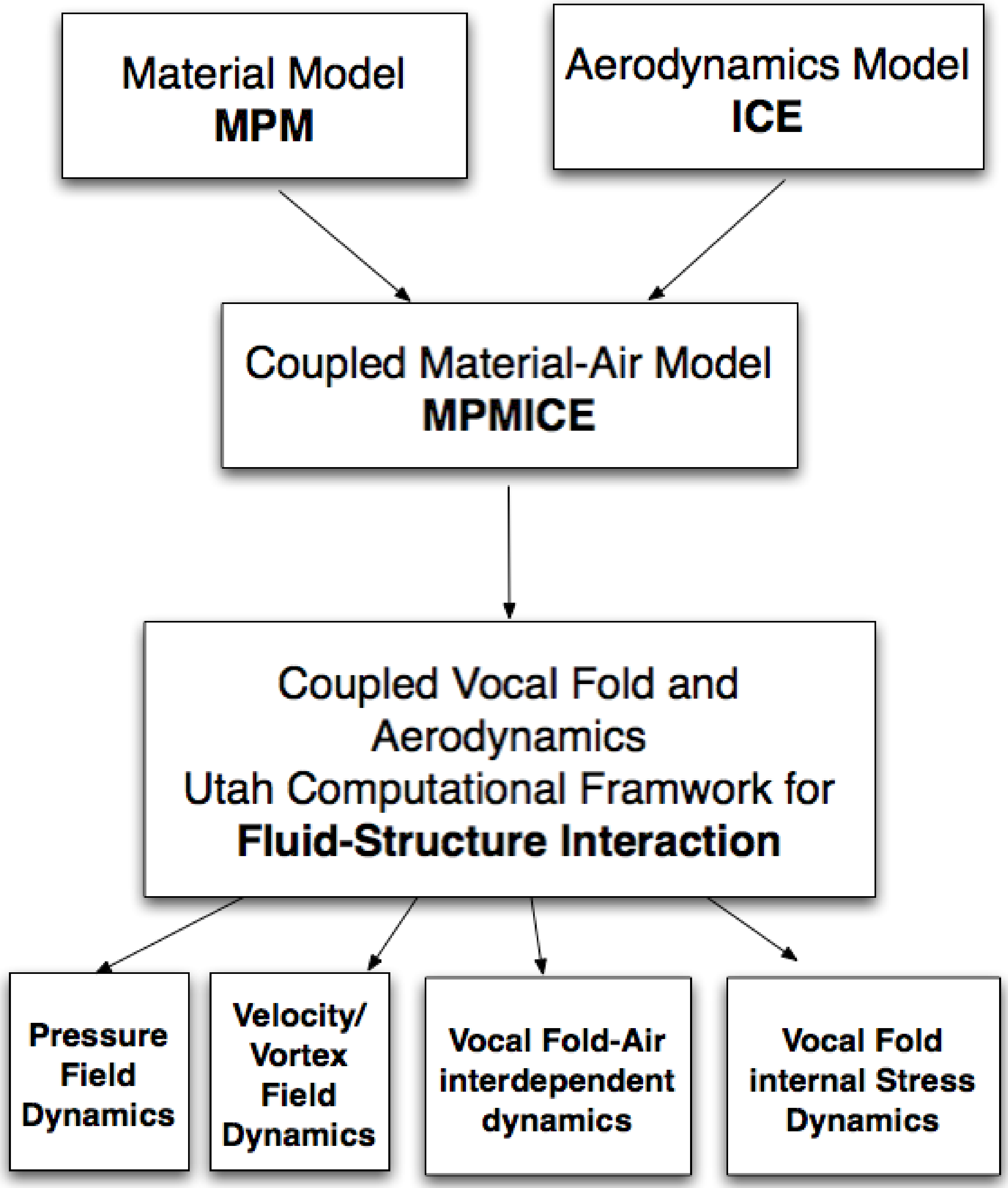
and $q_{rs} = H_{rs}\theta_r \theta_s (T_r - T_s)$ Internal energy exchange rate

and $\boldsymbol{\tau_r}$ is the deviatoric part of stress

$$\frac{1}{V}\frac{D_r(M_r v_r)}{Dt} = f_r^{\theta} \nabla \cdot \boldsymbol{u} + \theta_r \beta_r \frac{D_r T_r}{Dt} - f_r^{\theta} \sum_{s=1}^{N} \theta_s \beta_s \frac{D_s T_s}{Dt}$$

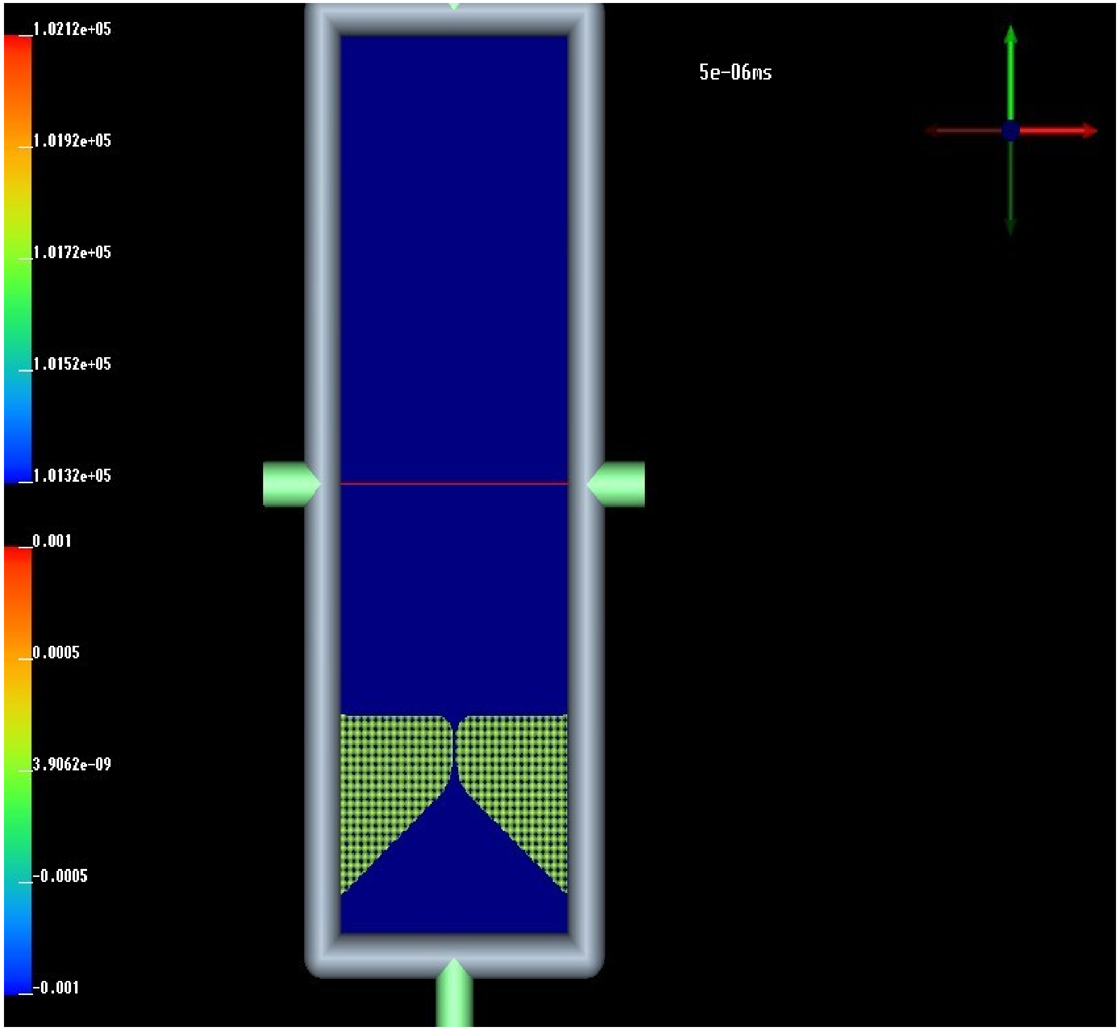
Evolution of Specific Volume

where $\boldsymbol{u} = \sum_{s=1}^{N} \theta_s \boldsymbol{u_s}$ mean velocity and $f_r^{\theta} = \frac{\theta_r \kappa_r}{\sum_{s=1}^{N} \theta_s \kappa_s}$


Material Model
MPM
Aerodynamics Model
ICE
Coupled Material-Air Model
MPMICE
Coupled Vocal Fold and Aerodynamics
Utah Computational Framwork for
Fluid-Structure Interaction
Pressure Field Dynamics
Velocity/ Vortex Field Dynamics
Vocal Fold-Air interdependent dynamics
Vocal Fold internal Stress Dynamics

A simplified one-material model showing geometry of vocal folds

- A simplified coronal slice
- Left and right vf are made of same material
- Particles are used to characterize the vocal fold material

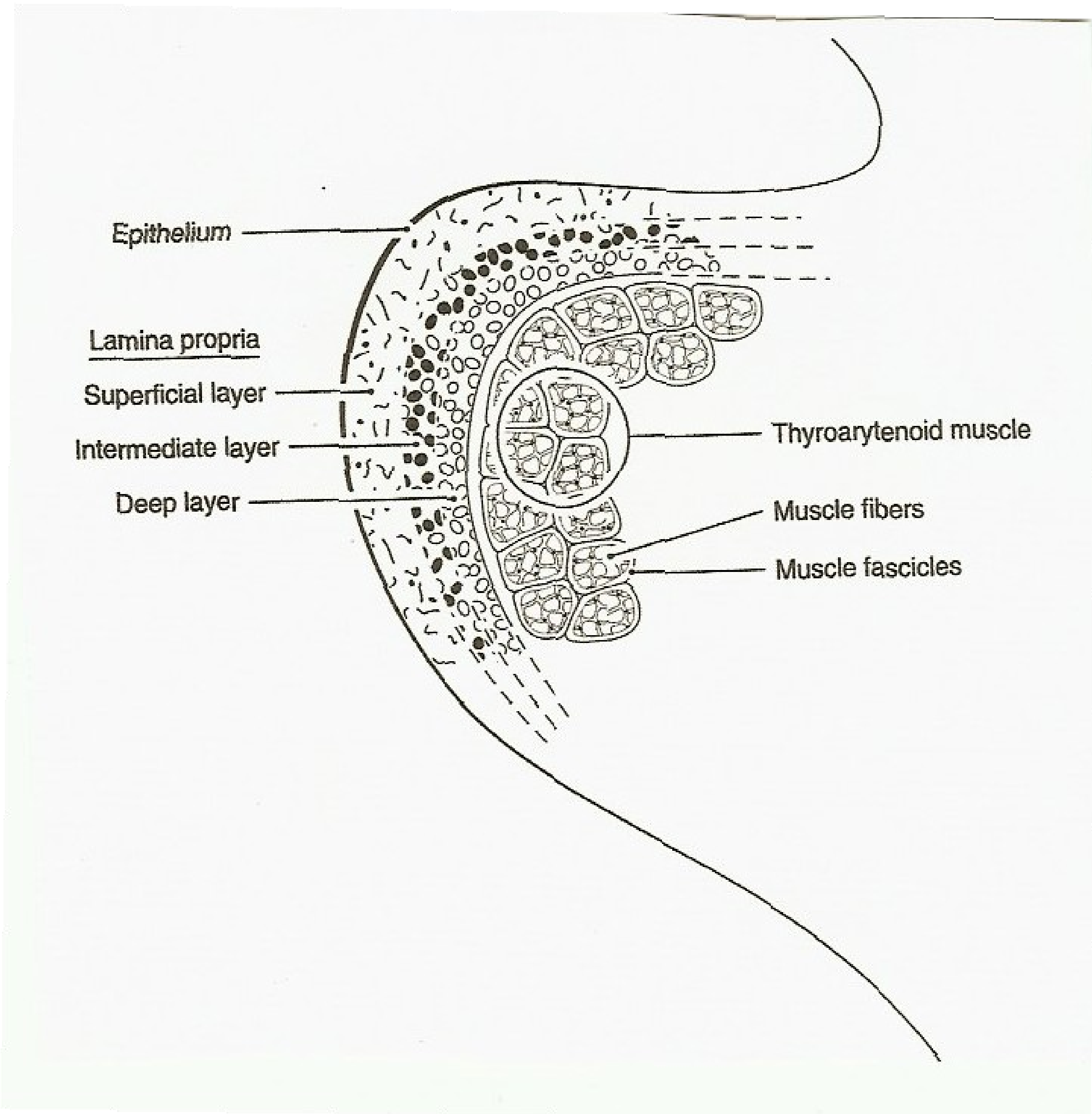


Material model

- Particles with spatially varying material properties
- Current simulations use Neo-Hook
- Initial particle distribution taken from standard coronal slice of mid-plane vocal fold
- Allows flexibility in material properties specification to more readily match histology

Sketch of Coronal Slice

- A step in the modeling is to abstract some simplified structures
- Complete generality given up so that a computer model can be realistically devised.

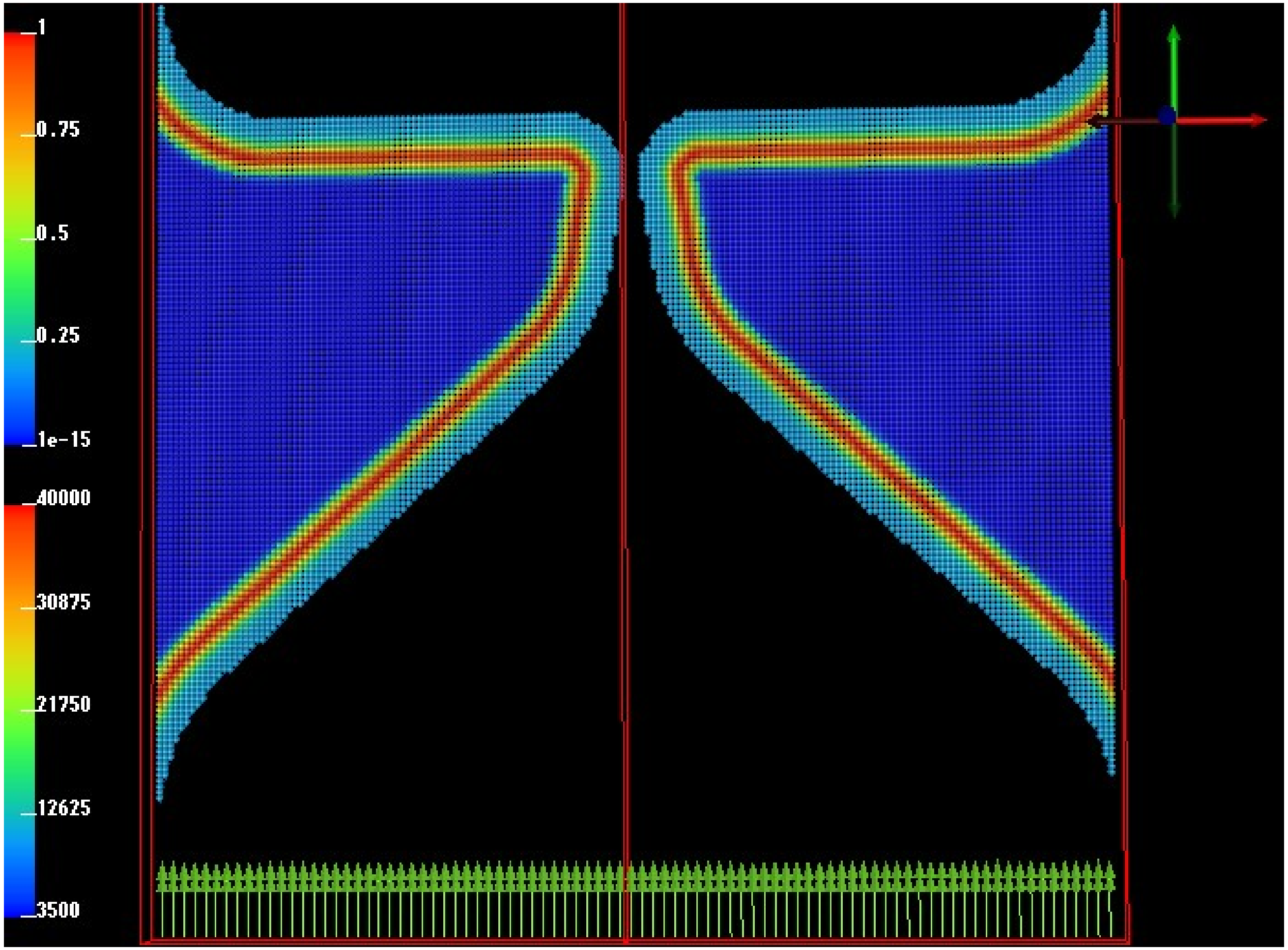


Three Layer Model: relation to histology

- Outermost layer = Mucosa: consists of the epithelium and the superficial layer of the lamina propria
- Middle layer = Ligament: consists of the intermediate and deep layers of the lamina propria
- Innermost layer = Deep layer: consists of the thyroarytenoid (vocalis) muscle

Example three-layer model

- 2D (z thickness small), each layer neo-hook
- mucosa, ligament, & muscle
- Variable shear modulus for each layer
- Same constant bulk modulus for all layers K=289 kPa



G_{mucosa} =10 kPa; $G_{ligament}$=30 kPa; G_{muscle}=3.5 kPa

Example Simulations

MPM:

- time integration: explicit
- interpolator: GIMP
- do grid reset: true
- Neo-hook with modification to map color to shear modulus in initial data set, constant bulk modulus
- Total particles: 11989

ICE:

- Advection: 2^{nd} order
- Pressure solve: implicit
- BC at inlet: Dirichlet pressure, Neumann for velocity, temp, and density
- BC at outlet: LODI for pressure, velocity, temp, density
- Resolution: 87 x 320

Movies

- 1. Close-up of the vocal folds with a graph of both the pressure and the opening width between the vocal folds as a function of time
- distribution of materials in distinct layers
- 2. movie showing the whole computational domain with vf and aerodynamics
- distribution of materials continuously varying

Current Developments

- Use nonlinear material models, since experiments show that materials are not neo-Hookean--materials are hyperelastic transverse isotropic
- Improve outflow boundary condition treatment
- Extract pressure signal at outflow
- Move to 3D !

Thanks！