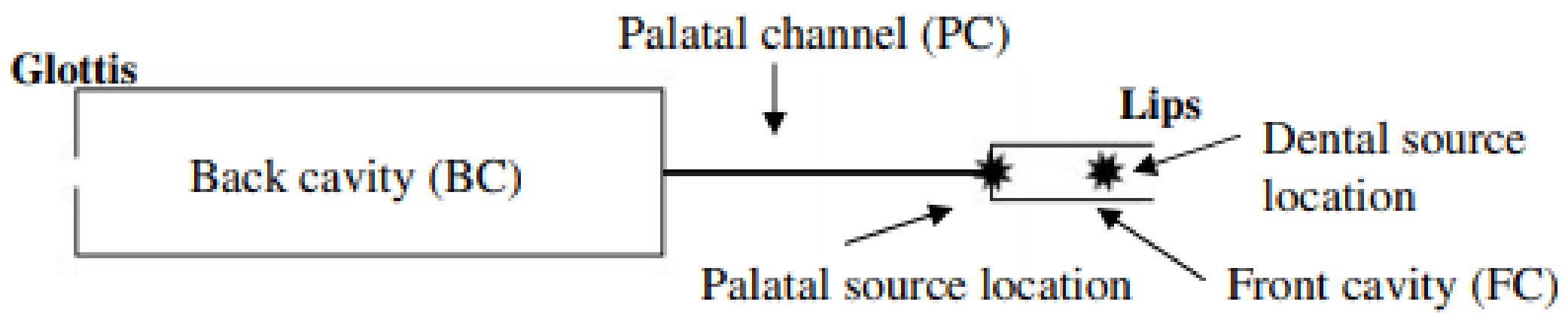
Relationships between turbulent flow configuration and sound source location of Japanese sibilant fricatives

Tsukasa Yoshinaga[1], Kazunori Nozaki[2] , Akiyoshi Iida[1]

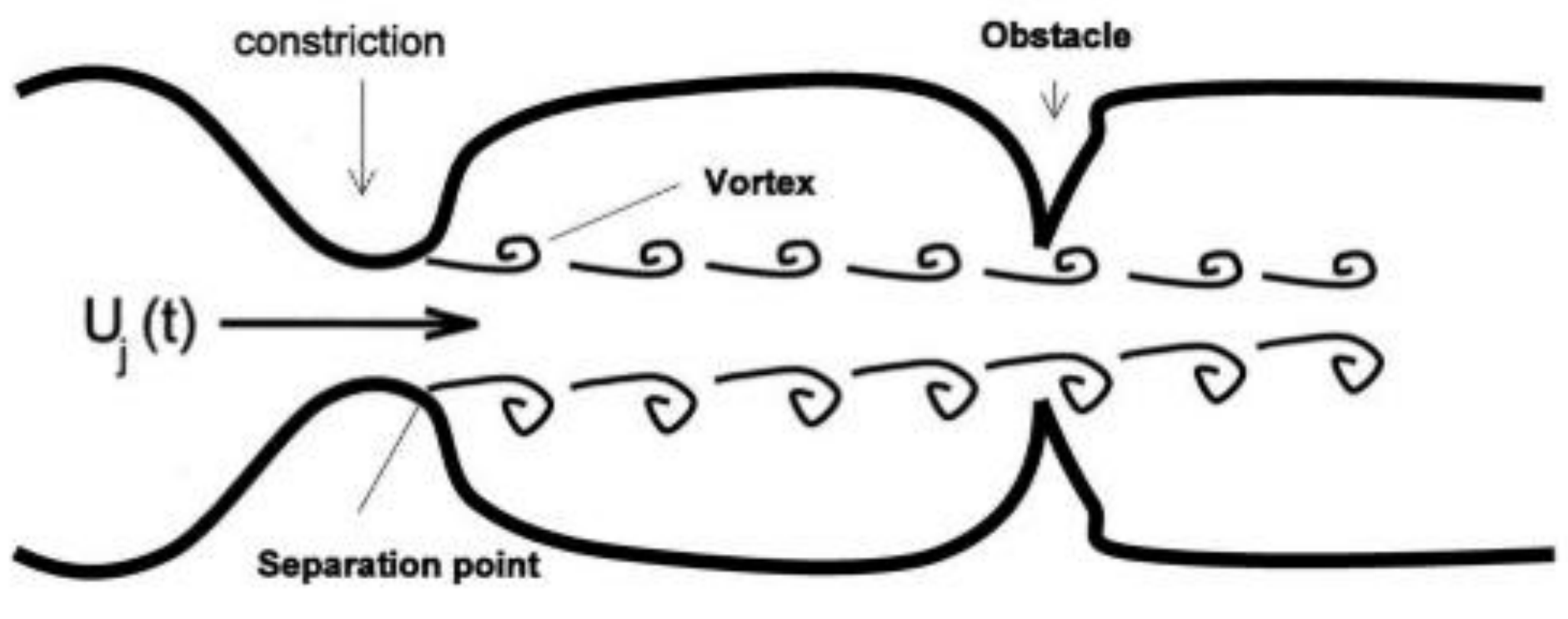
[1]Toyohashi University of Technology, [2]Osaka University Dental Hospital

1. Background

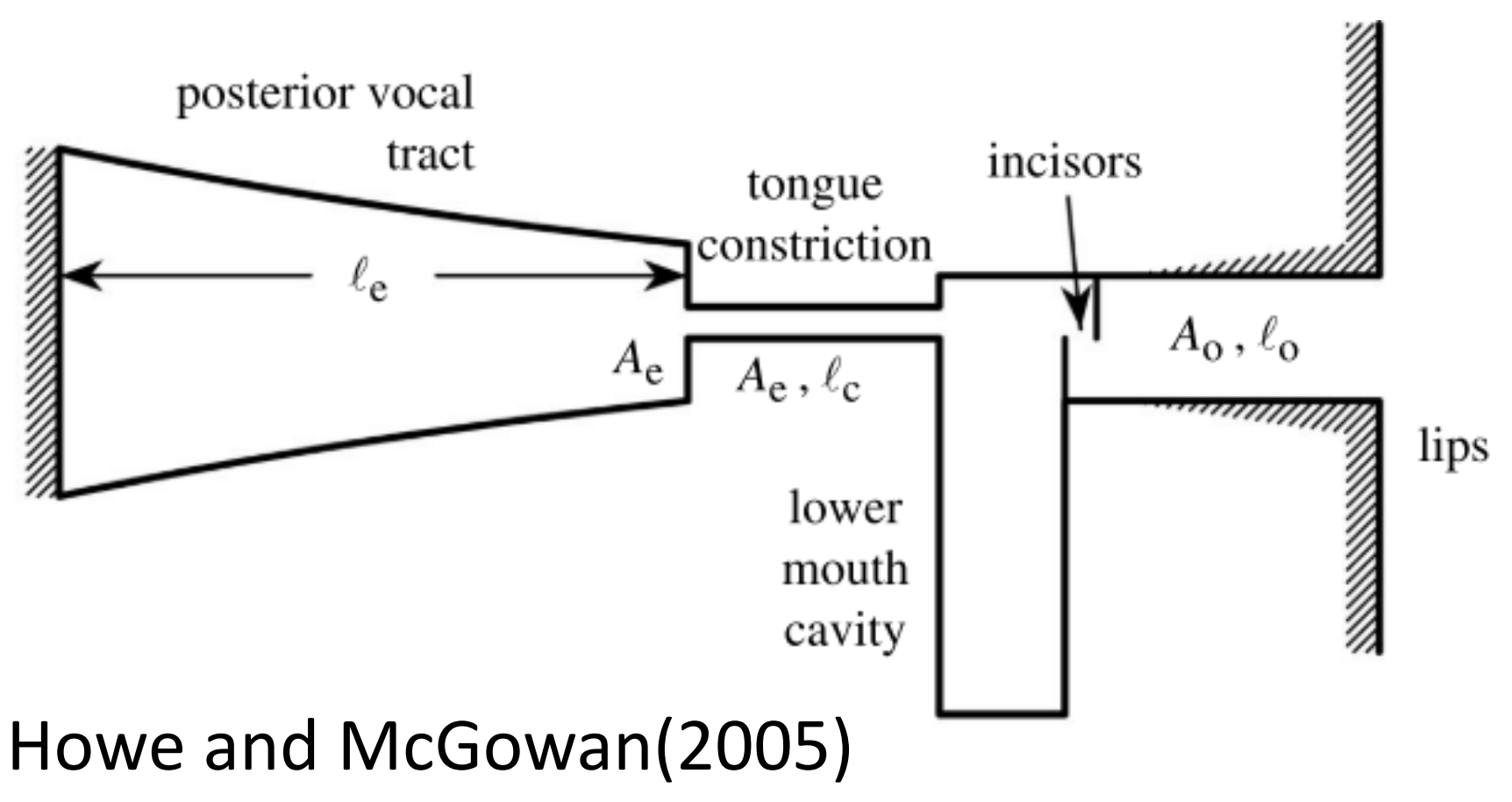
Fricative consonant [s] is known to be pronounced by using turbulent jet flow in a vocal tract. The jet flow is generated at the constricted flow channel formed by the tongue tip and alveolar ridge. The aeroacoustic source is mainly generated by turbulent vortices impinging on teeth and lip obstacles.



Toda and Maeda (2006)



Krane (2005)



Howe and McGowan(2005)

In previous studies, the sound source of sibilant fricatives was assumed to be located near the teeth in simplified models. However, we don't know the position of sources for each individual since the vocal tract geometry is different.

Purpose of this study

To clarify the relationship between the turbulent flow configuration and sound source location, the oral geometries of [s] were extracted from magnetic resonance imaging (MRI) and large eddy simulation (LES) was conducted for five male Japanese subjects.

Participants

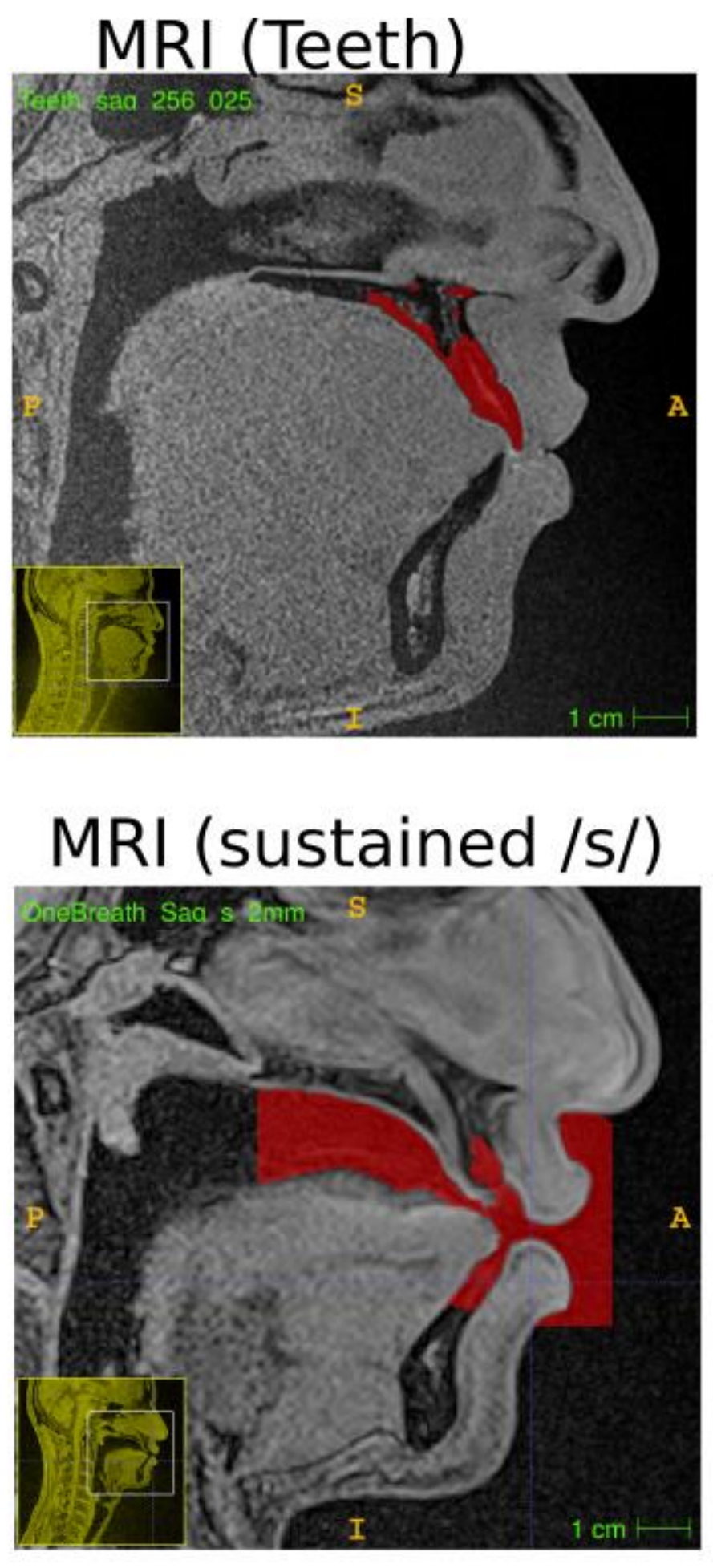
	Age	Sex		Age	Sex
Subject A	26	Male	Subject D	22	Male
Subject B	24	Male	Subject E	24	Male
Subject C	22	Male			

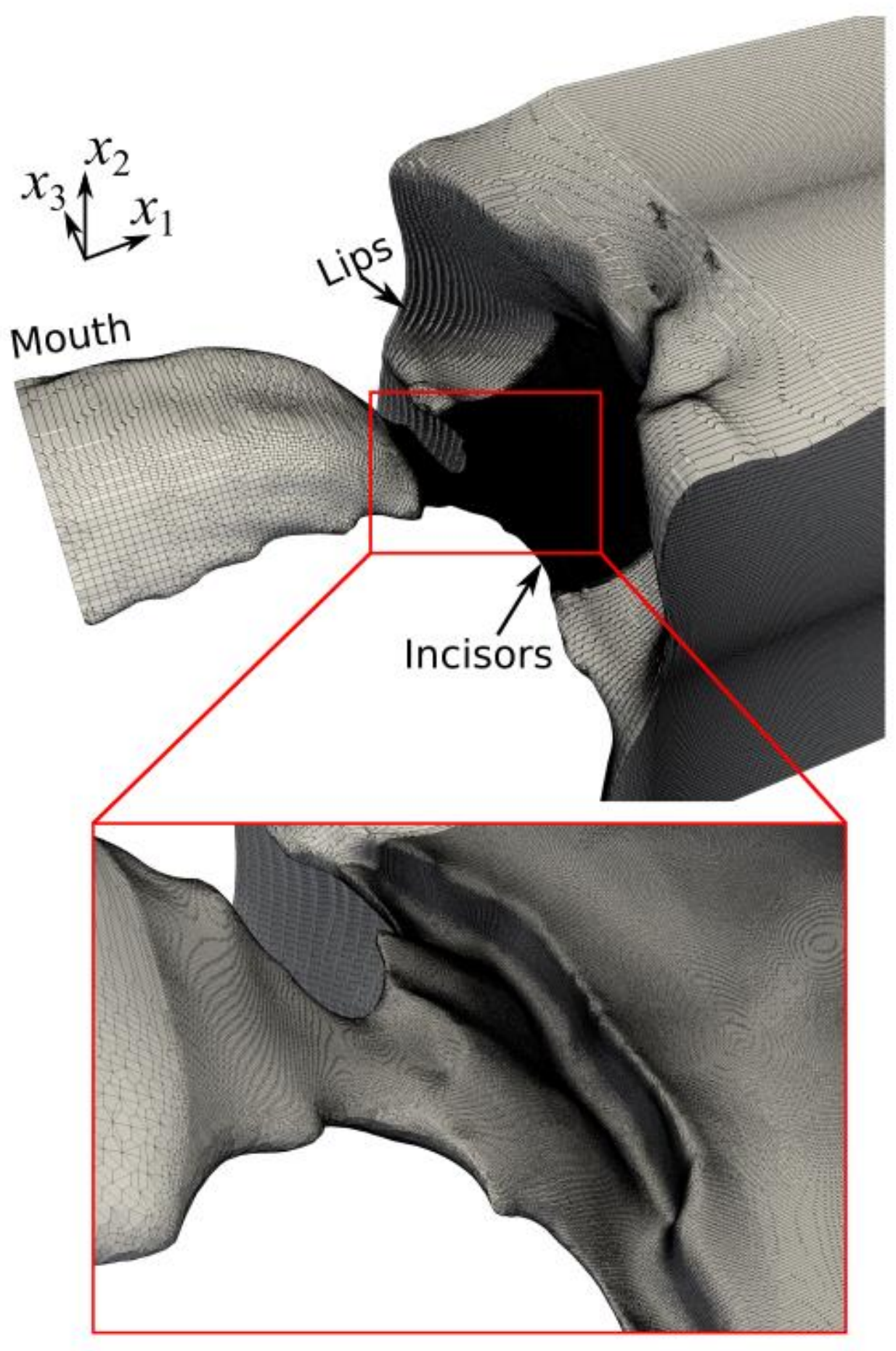
2. Materials and methods

Vocal tract geometry

MRI (Teeth)

MRI (sustained /s/)





Computational grids (40 million points)

Computational grids were constructed from MRI

Compressible flow Simulation

Governing equations

$$\frac{\partial \bar{\rho}}{\partial t} = -\frac{\partial \bar{\varphi}_j}{\partial x_j}$$

$$\frac{\partial \bar{\varphi}_i}{\partial t} + \frac{\partial \bar{\varphi}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial (\bar{\sigma}_{ij} - \tau_{ij})}{\partial x_j}$$

$$\frac{\partial \bar{\rho}\bar{E}}{\partial t} + \frac{\partial \bar{\varphi}_j \bar{E}}{\partial x_j} = -\frac{\partial \bar{p}\tilde{u}_j}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\alpha_{sgs}\frac{\partial \bar{e}}{\partial x_j}\right)$$

$$\bar{\rho} = \frac{1}{R\bar{T}}\bar{p}, \qquad \bar{e} = c_v \bar{T}$$

Flux: $\bar{\varphi}_i = \overline{\rho u_i}$

Total energy: $\bar{E} = \frac{1}{2}|\tilde{u}_i|^2 + \bar{e}$

LES stress tensor:

$$\tau_{ij} = \frac{2}{3}\bar{\rho}k_{SGS}\delta_{ij} - 2\bar{\rho}\nu_{SGS}\left(s_{ij} - \frac{1}{3}\delta_{ij}s_{ll}\right)$$

Viscous stress tensor:

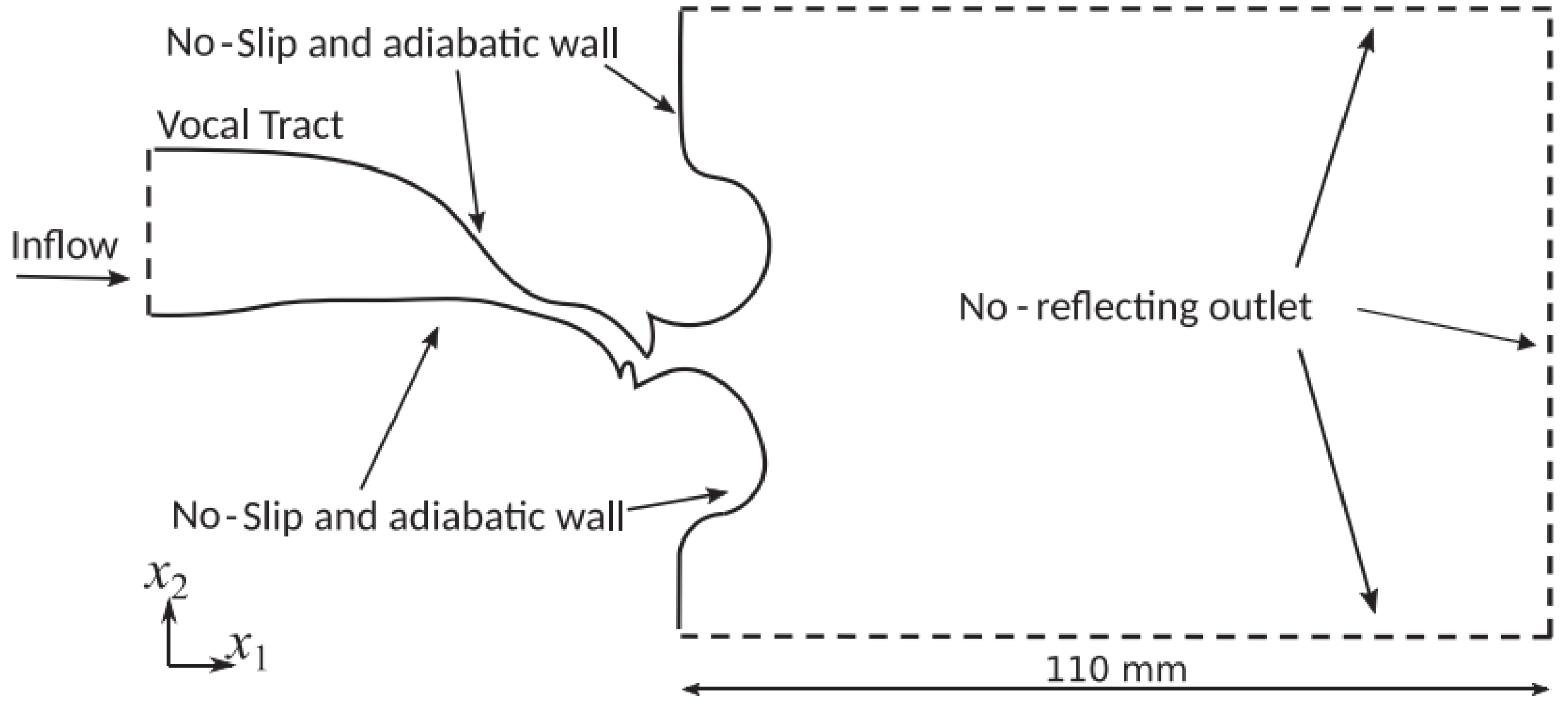
$$\bar{\sigma}_{ij} = 2\nu\bar{\rho}\left(s_{ij} - \frac{1}{3}\delta_{ij}s_{ll}\right)$$

Strain rate tenor:

$$s_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

Large eddy simulation of compressible flow is solve by FVM software OpenFOAM ver. 2.3.1

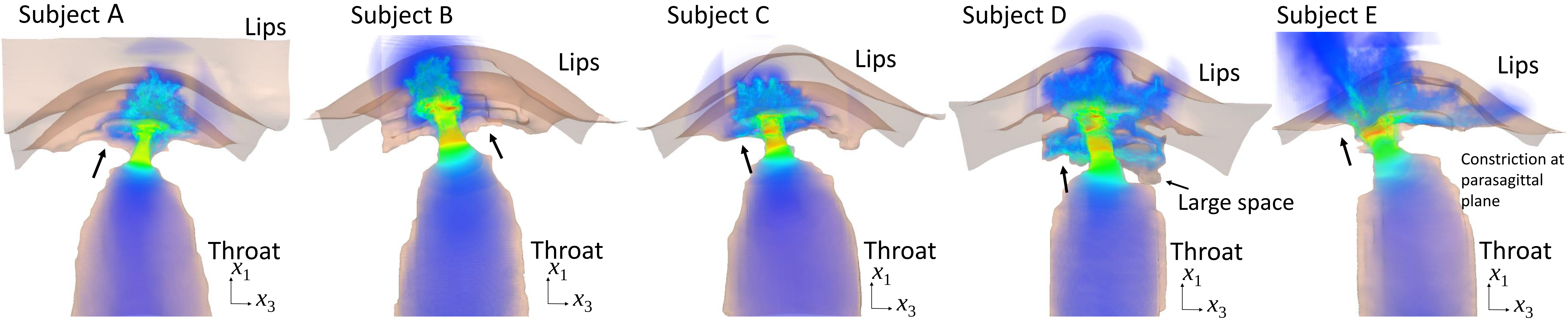
Boundary conditions



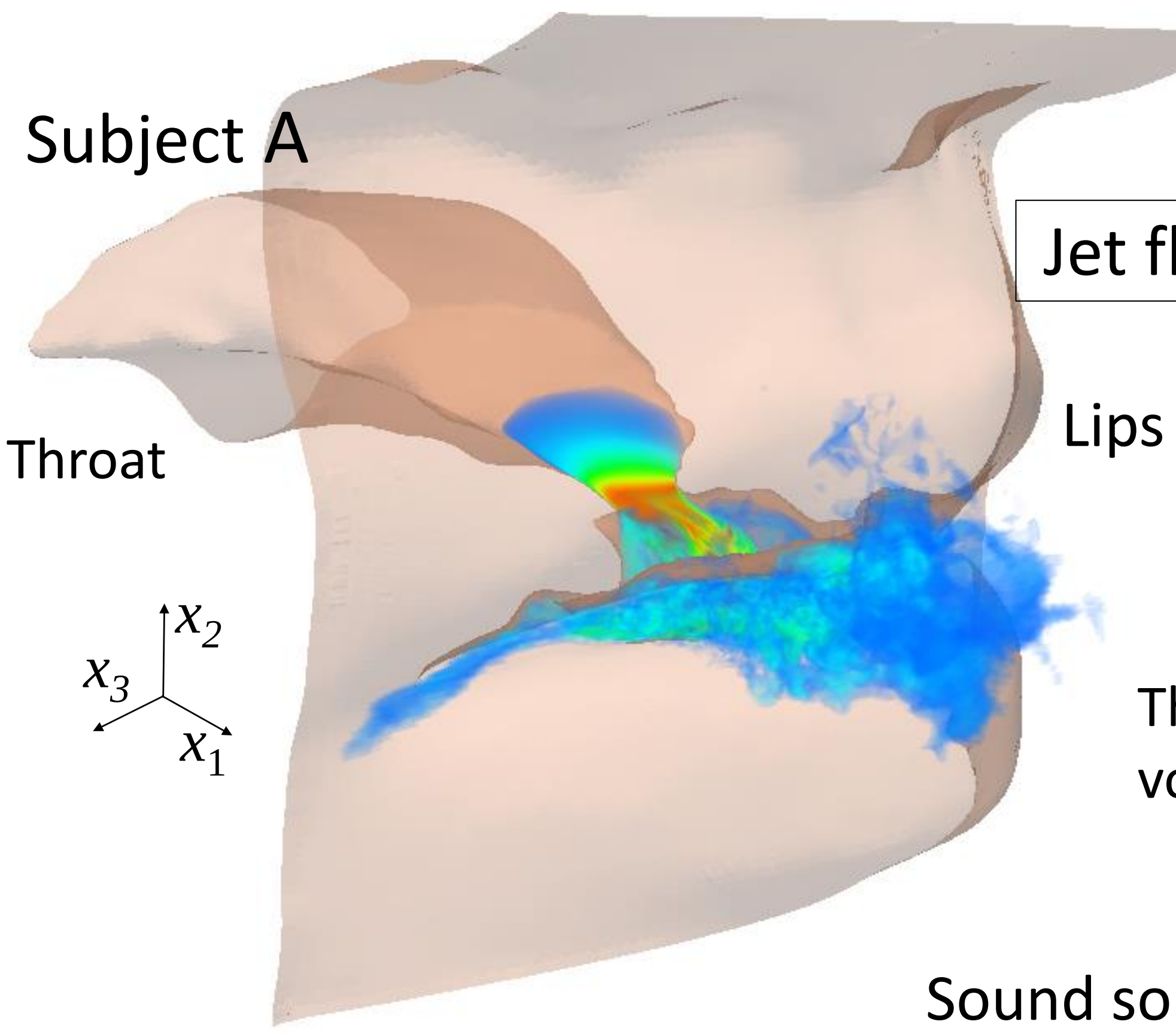
$\Delta t = 1 \times 10^{-7}$ s, $\bar{T}$ = 20 °C (at initial), c_v = 717 J/kg/K, R = 8.314 J/mol/K
Calculation time: 0.0132 s (1.32×10^5 steps)
Minimum grid size: 0.02 mm (CFL=1.62)
Uniform velocity with flow rate 123 to 350 cm³/s
FFT on pressure: average of 6 x 128 points, Hanning window

3. Results and discussion

Jet flow direction (views from head)

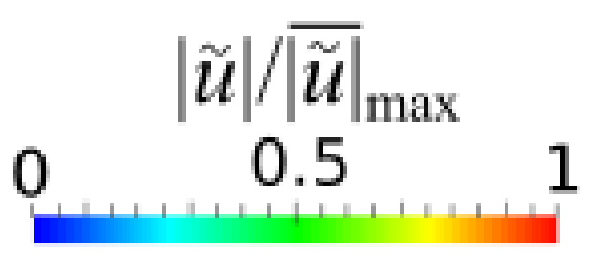


The every subject had inclined angles of jet flow from the midsagittal plane. Subject D had a large space between the tongue tip and lower jaw, while the constriction of subject E was at the parasagittal plane.



Jet flow (front view)

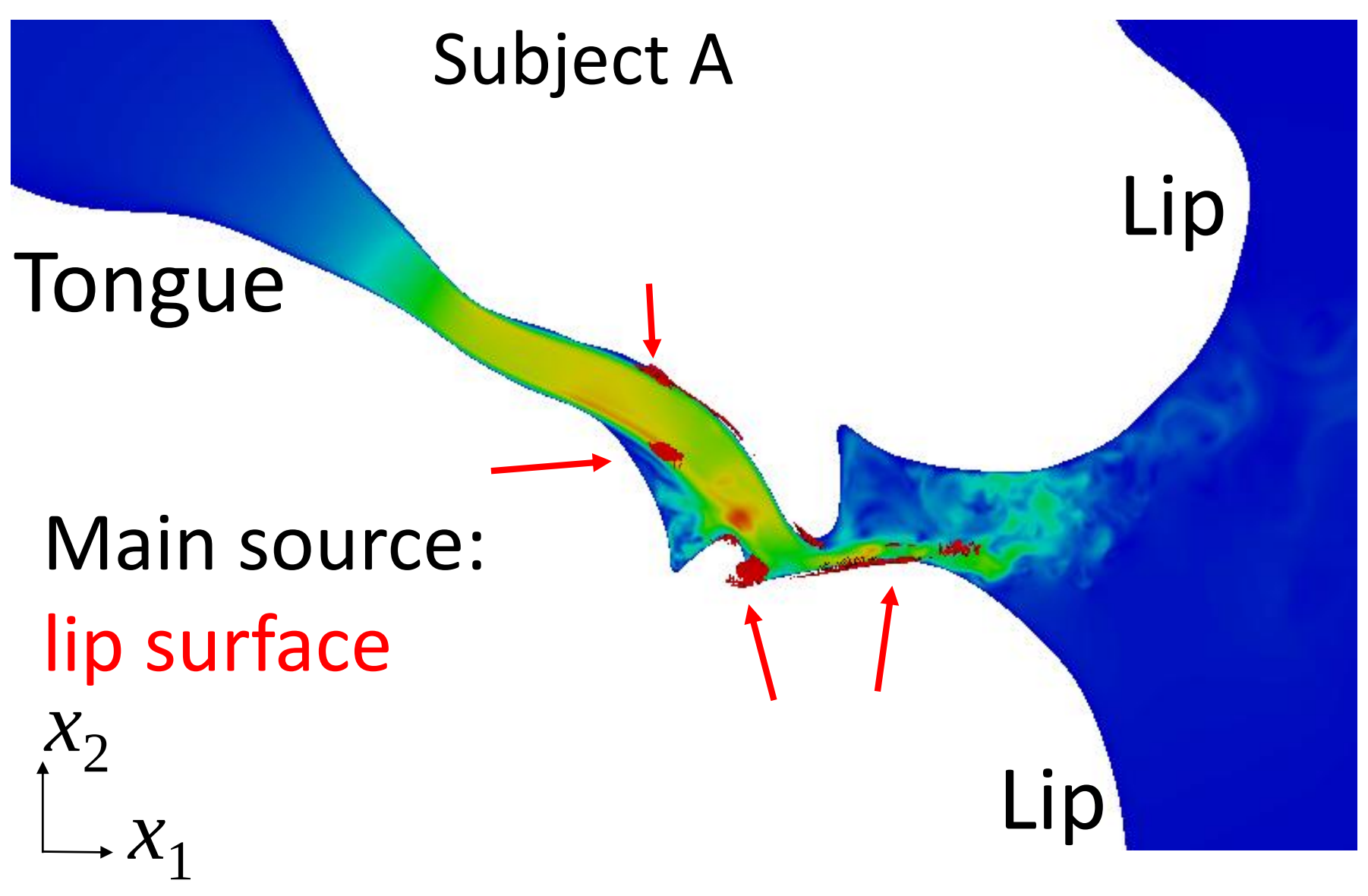
The color from blue to red shows the flow velocity.



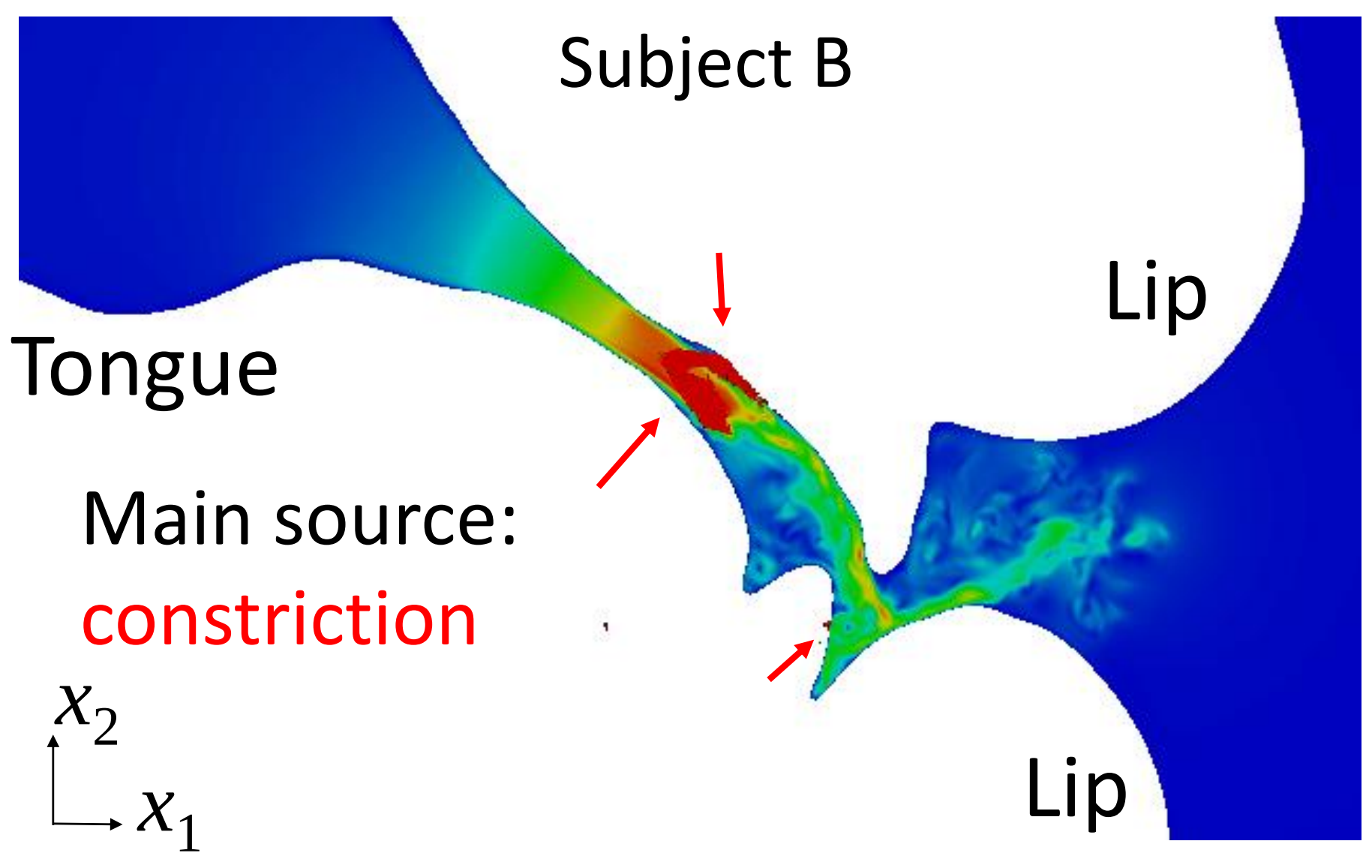
The velocity fields are shown by volume rendering.

Sound source: $\frac{\partial^2 \rho u_i u_j}{\partial x_i \partial x_j} > 10^{10}$ kg/m²s²

Sound source locations (red) in the flow field on sagittal planes

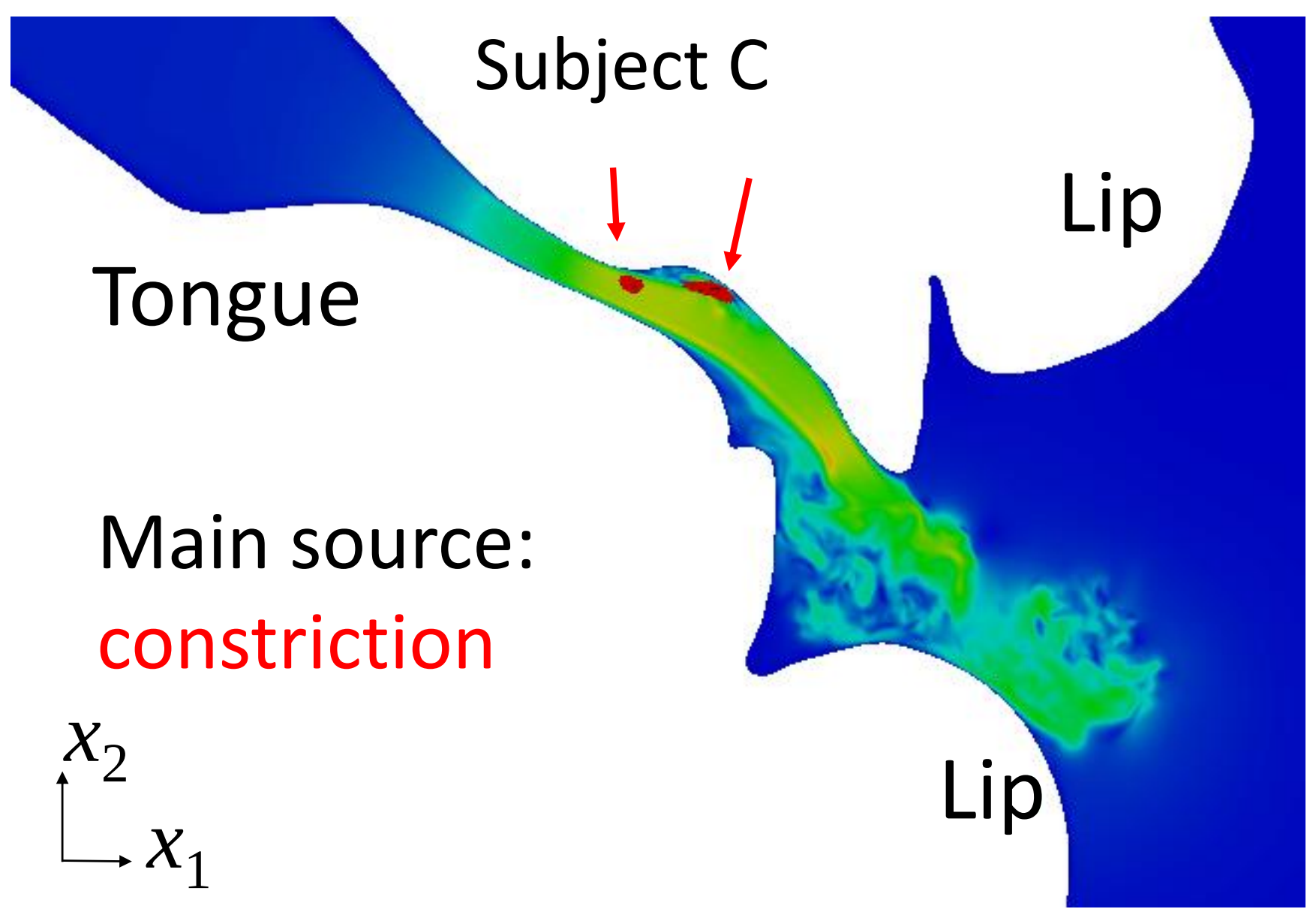


Main source: lip surface

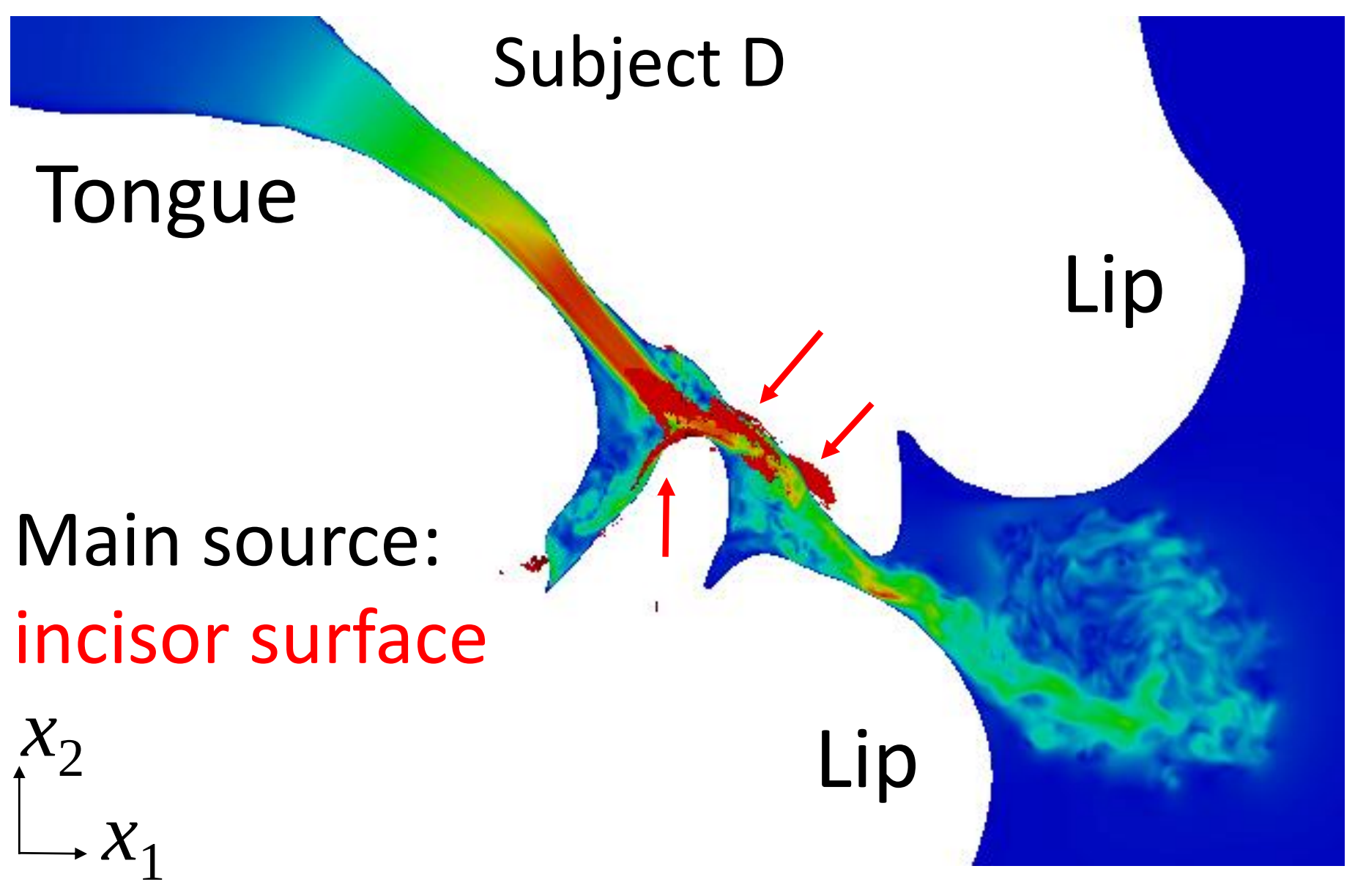


Main source: constriction

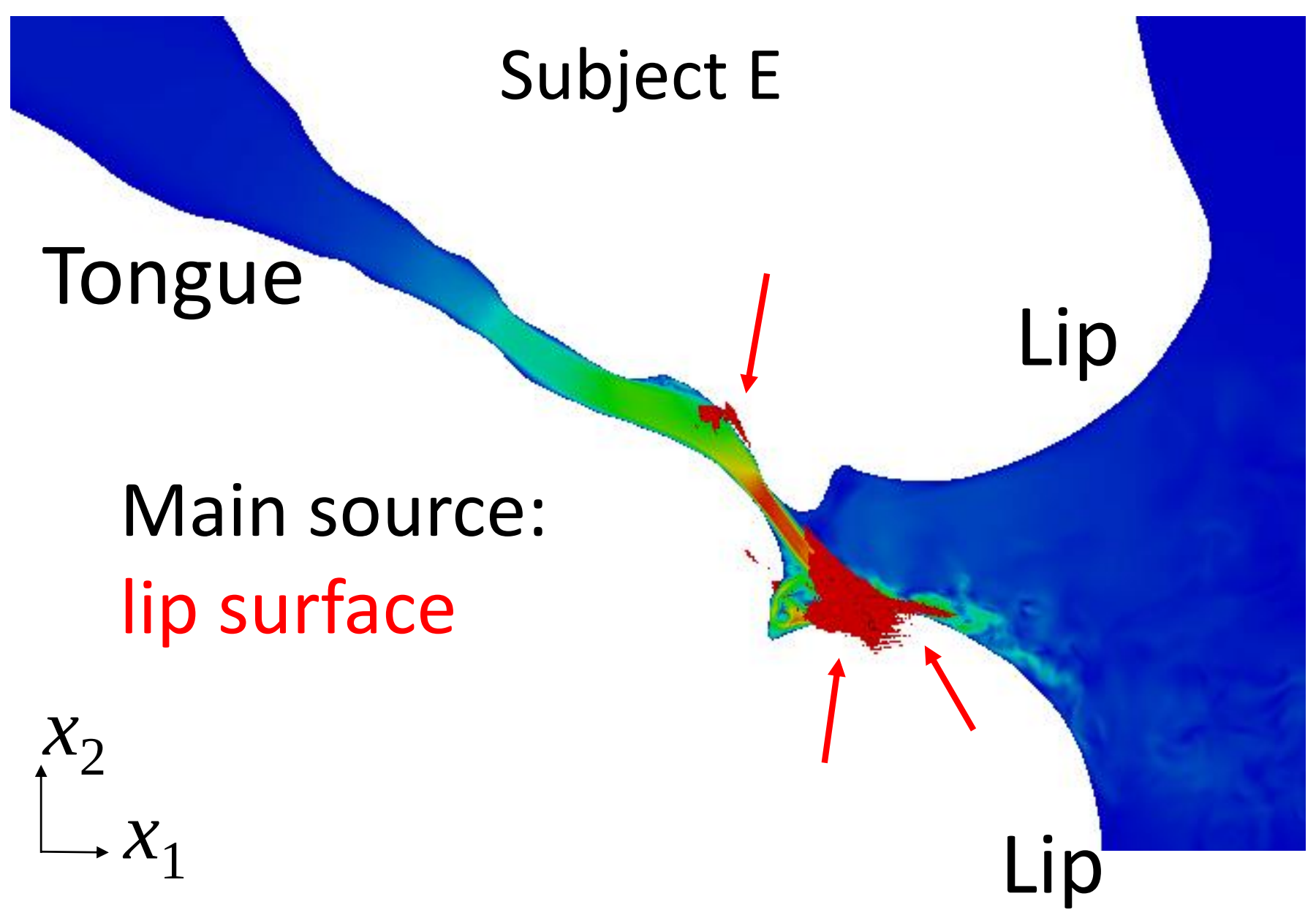
The main sound source appeared near the lip surface in subject A and E with relatively small flow channel, whereas the source appeared near the constriction in subject B and C with relatively large channel. The subject D had a sublingual cavity and the source appeared near the incisor surfaces.



Main source: constriction



Main source: incisor surface



Main source: lip surface

4. Summary

With the flow simulation, we found that the sound source of [s] appeared near the surface of lips in the subjects who had a relatively small flow channel downstream from the constriction, whereas the sound source appeared at the separation of the constriction in the subjects who had a relatively large flow channel downstream from the constriction.

References

Howe, M. S., & McGowan, R. S. (2005). Aeroacoustics of [s]. *Proc. Royal Society A: Mathematical, Physical and Engineering Sciences*, *461*(2056), 1005-1028.
Krane, M. H. (2005). Aeroacoustic production of low-frequency unvoiced speech sounds. *The Journal of the Acoustical Society of America*, *118*(1), 410-427.
Toda, M., & Maeda, S. (2006). Quantal aspects of non anterior sibilant fricatives: a simulation study. *Proc 7th ISSP*, 573-580.
Yoshinaga, T., Nozaki, K., and Wada, S. (2019). "Aeroacoustic analysis on individual characteristics in sibilant fricative production," J. Acous. Soc. Am. 146, 1239-1251.

Acknowledgement

This work was supported by MEXT as "Priority Issue on Post-K computer" (hp20123), JSPS KAKENHI (T15K013660), and JSPS Grant-in-Aid for Scientific Research on Innovative Areas (A18H050770).