Comparison of acoustic rhinometry, rhinomanometry and lattice Boltzmann simulation of nasal air flow

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Abstract. The accuracy of nasal air flow fluid flow simulations is important to support surgeons in the preoperative planning phase. Lattice Boltzmann (LB) simulations of the nasal air flow based on CT (swollen mucosa) and MRI (detumesced mucosa) datasets of one patient with breathing problems are compared to acoustic rhinometry and rhinomanometry datasets. Results show that LB is able to simulate the rhinomanometry curves of one patient with an average root mean square error of 69 Pa. LB simulations based on MRI (average RMSE, 34 Pa) are in better accordance to rhinomanometry than LB simulations based on CT (average RMSE, 103 Pa) to rhinomanometry. Segmentation of MRI (average RMSE, 0.72 cm^2) is in better accordance to the acoustic rhinometry than segmentation of CT (average RMSE, 1.93 cm^2) to the acoustic rhinometry. Results show that swelling/detumesced mucosa can be detected with the LB simulations based on CT/MRI datasets.
This initial study shows that computational fluid dynamics calculations can reproduce features used in routine ENT diagnosis of breathing. A validation study with more patients is under way.

Keywords: nasal air flow · rhinomanometry · lattice Boltzmann.

1 Purpose

Depending on the experience of the surgeon, surgery success rate to improve nasal breathing, in different studies, is in average between 60 % and 80 % [1]. Numerical fluid flow simulations are already state of the art [2] to simulate nasal air flow, but validation is needed. Based on nose like models, experimental validation with laser Doppler anemometry (LDA) and particle image velocimetry

(PIV) is available [2]. PIV, LDA and the anatomic 3D-model generation technique includes measurement error. A comparison between lattice Boltzmann (LB) simulations based on magnetic resonance imaging (MRI) with detumesced mucosa, computed tomography (CT) with swollen mucosa and acoustic rhinometry and rhinomanometry measurements is shown. Rhinomanometry measures pressure drop and flow rate during inspiration and expiration through the nose, whereas acoustic rhinometry determines the nasal air flow cross-section area. The accuracy of the segmentation process is determined. Furthermore, the LB fluid flow simulation results to predict rhinomanometry curves are presented.

2 Methods

2.1 Segmentation of the CT and MRI dataset

An anonymous adult human CT dataset (Siemens Somatom, beam current 88 mA, convolution kernel H30s, spatial resolution 0.3 x 0.3 x 0.3 mm^3) with a swollen mucosa was used for the study. An anonymous human MRI dataset (Siemens Sonata,T1-weighted, ISO IR 100, sequence name *tfl3d1, imaging frequency 63.679195 MHz spatial resolution 0.9375 x 0.9375 x 1.2 mm^3) with detumesced mucosa was used for the study. Segmentation of the nasal cavity and paranasal sinuses was performed in 3D Slicer [4] with -460 HU [5]. The MRI dataset was thresholded to air. The surface geometry file [4] that was saved in stl-file format. At the nasopharynx and the nostrils, cuboids with the dimensions of 60 x 40 x 20 mm^3 were added to the nasal air flow region to set inlet/outlet fluid flow boundary condition for the LB simulations. For comparison with rhinomanometry data lone nostril was blocked in the stl file and saved.

2.2 Lattice Boltzmann (LB) simulation

Nasal air flow was simulated with Sailfish CFD [3] on high-end graphic cards (GPUs) with computation times < 5 minutes. For turbulence modeling, the large eddy simulation (LES) with Smagorinsky subgrid (constant $c_s = 0.14$) [3] was used. Proofed by calculated Reynolds number (Re) [6] at the inlet/outlet boundary condition and comparison to critical Re of pipe flow with 2300 [6], turbulence was relevant at a flow rate $> 300\,ml/s$. Δx was set to 0.3 mm so that the LB simulation results were mesh independent [7]. Simulated flow rate boundary conditions were taken from Rhinomanometry 0 - 600 ml/s (50, 100, 150 ml/s, ..., 600 ml/s) for inspiration and expiration, left and right nostril, respectively. Sailfish CFD NTRegularizedVelocity, NTDoNothing, NTWallTMS [3], were used to specify outlet, inlet and wall boundary condition. The simulations were stopped when a stationary pressure drop between inlet and outlet boundary condition was achieved (0.0125 seconds). The Rhinomanometry curves were approximated by regression with the function $\Delta p = a_1\dot{V} + a_2\dot{V}^2$ to determine the coefficients a_1 and a_2 based on the Bernoulli equation [6], Δp is the pressure drop and $\dot{V}$ is the flow rate. For comparison with the simulations, the root mean square error (RMSE) [8] was used.

2.3 Cross-section determination at CT/MRI datasets for comparison with acoustic rhinometry

The coronal air flow cross sections of the main nasal cavity based on CT/MRI datasets were determined in 3D Slicer [4]. The origins were defined in the geometric center of the coronal inlet of the nostrils and evaluated up to 90 (0, 5, 10 ... 90 mm). The paranasal sinuses were excluded. Acoustic rhinometry curves were not approximated by a continuous function, since for every distance a unique cross-section was found. For comparison between acoustic rhinometry and segmentation the RMSE was used [8].

3 Results

3.1 Rhinomanometry vs. simulation

Fig. 1 left shows the simulation results in overlay to rhinomanometry data of the same patient. Two rhinomanometry measurements were performed: Swollen mucosa with a higher pressure drop, detumesced mucosa with a lower pressure drop. The pressure drop RMSE of all simulated points of swollen right (side nasal cavity) was 60.25 Pa, swollen left was 148.43 Pa, not swollen right was 8.40 Pa and not swollen left was 58.23 Pa. The quality of the simulation can be inferred from the difference of the simulated points to the fitted medical data (left panel, black line).

3.2 Acoustic rhinometry vs. segmentation

Fig. 1 right shows the segmentation results in overlay to acoustic rhinometry measurements. The results show that MRI segmented data were closer to the corresponding measurements with detumesced mucosa. The CT data was closer to acoustic rhinometry with swollen mucosa. The quality of the simulation can be inferred from the difference of the simulated points to the measured medical data (right panel, solid lines). The cross-section RMSE of left cavity, not swollen, was $0.81\,cm^2$, swollen $2.32\,cm^2$; right: not swollen $0.63\,cm^2$, swollen $1.54\,cm^2$.

4 Conclusion

In addition to the numerical investigations of the nasal air flow [2], which are already state of the art, our fluid flow simulation based on LB is able to simulate clinical rhinomanometry data well with an average RMSE of 69 Pa. LB simulations based on MRI (average RMSE, 34 Pa) were in better accordance to rhinomanometry than CT (average RMSE, 103 Pa). Segmentation of MRI (average RMSE, $0.72\,cm^2$) was in better accordance with acoustic rhinometry measurement than CT (average RMSE, 1.93 cm^2). These preliminary results show that LB simulations are apt to simulate clinical rhinomanometry data. Moreover, LB simulations have the potential to replace rhinomanometry. This method, however, must be proofed with more patient datasets which is under way.

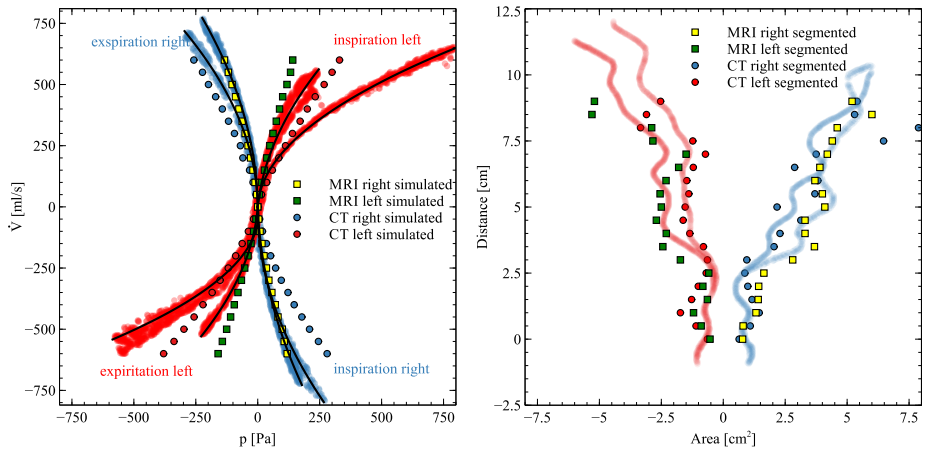

Fig. 1. Left: Comparison of rhinomanometry measurement data with LB simulation results based on CT and MRI dataset of the same patient. On the abscissa the pressure drop between nostril and throat is in Pa, on the ordinate the flow rate ($\dot{V}$) in ml/s is depicted. Right: Comparison of acoustic rhinometry measurement data with segmentation results of the same patient. The distance in cm is the acoustic rhinometry distance from the measurement head, at the simulations those are in coronal direction from nostril. Black lines are Bernoulli approximations [6] by regression.

References

1. Gillman, G. S., Egloff, A. M. & Rivera-Serrano, C. M. Revision septoplasty: A prospective disease-specific outcome study. Laryngoscope 124, 12901295 (2014)
2. Arbour, P., Bilgen, E. & Girardin, M. Experimental study of velocity fields in a human nasal fossa by laser anemometry. Rhinology 23, 201207 (1985)
3. Januszewski, M. & Kostur, M. Sailfish: A flexible multi-GPU implementation of the lattice Boltzmann method. Computer Physics Communications 185, 23502368 (2014)
4. Fedorov, A, et al. 3D Slicer as an Image Computing Platform for the Quantitative Imaging Network. Magnetic Resonance Imaging Nov;30(9), 18 (2012)
5. Nakano, H. et al. A new method for determining the optimal CT threshold for extracting the upper airway. Dentomaxillofacial Radiology 42, 13 (2013)
6. Landau, L. D. & Lifshitz, J. M. Fluid Mechanics - Third Revised English Edition. (Pergamon, 1959)
7. Berger, M. et al. A mesh convergence study on LB flow simulations of the nasal geometry with horizontal cut. Minisymposium Verfahrenstechnik (2017)
8. Giri, P. K., Banerjee, J., Introduction to STATISTICS Sixth edition, Academic Publisher KOLKATA-700 073 (2008)