



## Improvement of Tomo-PIV Analyses in the Nasal Cavities

Sandra Melina Tauwald<sup>1,2,\*</sup>, Florian Erzinger<sup>2</sup>, Maurizio Quadrio<sup>3</sup>,  
Markus Rütten<sup>4</sup>, Christian Stemmer<sup>5</sup>, and Lars Krenkel<sup>1,2</sup>

1: Regensburg Center of Health Sciences and Technology (RCHST), Germany  
2: Dept. of Biofluidmechanics, Regensburg University of Applied Sciences (OTH),  
Germany

3: Dept. of Aerospace Science and Technology, Politecnico Milano, Italy

4: Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR),  
Germany

5: Chair of Aerodynamics and Fluid Mechanics, Technical University of Munich (TUM),  
Germany

\* Correspondent author: melina.tauwald@oth-regensburg.de

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The nasal cavities act as the main gateway to the entire respiratory system and thus play a pivotal role in respiratory homeostasis. The primary physiological function is for humidifying, warming, and particle filtering (Zubair et al., 2011). Indispensable for the physiological function is the sufficient contact of the respiratory air with the mucosa, the lining epithelium of the airways (Mlynski, 2013). Otorhinolaryngologists need detailed information of the flow regime in the patient-specific geometry in order to make a suitable diagnosis, preoperative planning, and thus achieve a successful surgery result. While the complex morphological structure of the nasal passageways is limited in access, the interaction of its anatomical form and its function requires investigations through either computational fluid dynamics (CFD) or in-vitro experiments (Doorly et al., 2008). The literature reveals investigations comprising CFD and/or experimental studies (Cozzi et al., 2017; Hörschler et al., 2006; Lintermann & Schröder, 2019). Nevertheless, the suitability of these investigations for the implementation to the medical field needs careful consideration. Emerging problems range from simplified geometries, neglecting the effects of cyclic respiratory flow, to the application of a suitable computational model (Zubair et al., 2011). These problems represent major challenges, and might be overcome by the hereinafter described tomo-PIV setup and investigations.

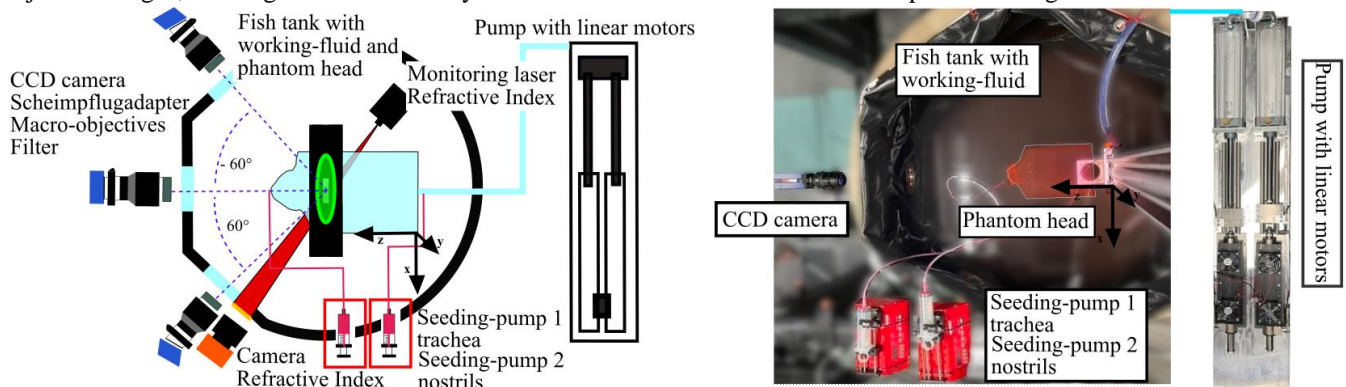


Figure 1. Experimental setup (sketch left, photograph right) in a top view including the RIM, the tomo-PIV setup and the flow inducing pump system.

A silicone model of the upper respiratory tract, based on a computer tomographic (CT) scan (ethical approved) of a person's head has been manufactured. The experimental setup (figure 1) includes the model placed in a fish tank filled with working-fluid (WF) attached to a traversing unit. Three aspects have to be highlighted: the refractive index (RI) matching (RIM), the tomo-PIV setup, and the flow inducing part. The RIM monitoring contains a line laser placed vis-à-vis the 60° angled porthole. After passing the Region of Interest (RoI), the light sheet exiting the fish tank is visualized on a scaled paper and captured by a camera. Thereby, a kinked laser line on the scaled paper indicates a non sufficient matching of the RIs of the geometry and the WF. The tomo-PIV setup contains three CCD-cameras (1600x1200) equipped with macro objectives, Scheimpflug adapters, and cut-off filters. The tracer particles (20-50  $\mu\text{m}$ ) are seeded by two syringe pumps, either via the trachea or via the nostrils, depending on the cycle state, and illuminated by a double-pulsed laser. The initial plate calibration of the cameras is refined in each RoI by a Volume Self Calibration (VSC). The volumetric reconstruction and vector calculation is done with a final window size of 40 voxels and a maximum expected displacement of 24 voxels. Images are captured by several inter double-frame rates (PIV-dts) depending on the cycle state and the geometry's shape. Within the flow inducing part, comprising a linear motor driven piston pump, the induced flow rate is based on test persons data adjusted by Reynolds and Womersley similarity, leading to a cycle period of 24.8 seconds, including the expiration part of 11.72 seconds. Thereby, peak flow rates

are achieved at 6.0 seconds (0.370 l/s) for expiration and 17.7 seconds (-0.372 l/s) for inspiration. All components are centrally controlled by a programmable logic controller. The in-place RIM monitoring shows the best results within a RI of 1.4139. The final achieved RoI reaches a size of 34 mm x 34 mm x 6 mm with a scale factor of 29 pix/mm.

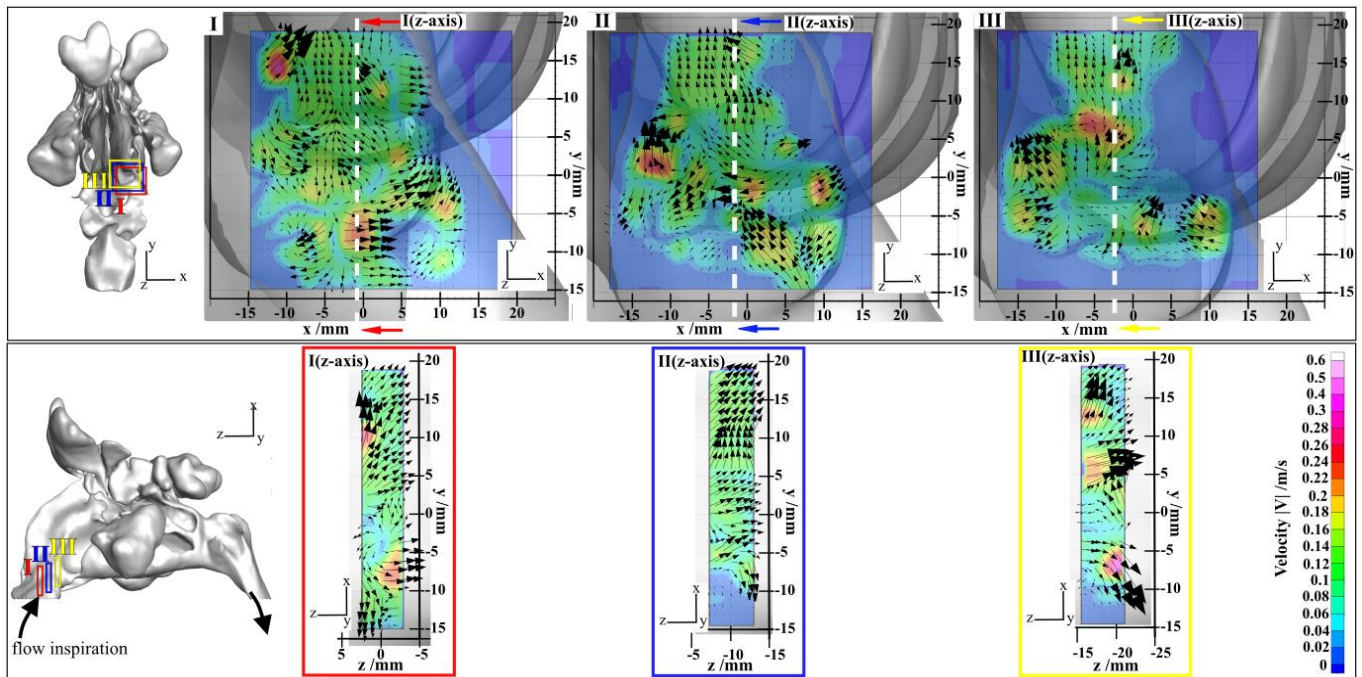


Figure 2. Exemplary velocity distributions in three different RoIs. The left part indicates the positions in the geometry. The right part shows the velocity magnitudes, colour-coded, in a coronal section (upper part) and in a sagittal section (lower part).

While non-free-of-sight tomo-PIV investigations are sensitive to optical distortions, a precise RIM is necessary to achieve a successful calibration. The in-place RIM monitoring provides a precise RI control, leading to VSC-errors lower than 0.1 pixel. The defined seeding strategy of this study, adapted to the respective cycle phase enables a nearly homogenous tracer particle seeding and a sufficient seeding density. The marker particles in the geometry and a defined coordinate system of the geometry-moving traversing unit allows a matching of the small investigated RoIs into the micro CT-scan (STL-data, 11 mio faces) of the silicone head. Figure 2 shows velocity fields in three RoIs during inspiration at 15.9 seconds in the cycle, comprising a flow rate of -0.303 l/s and analyzed by a PIV-dt of 7 ms. The RoIs are located at the right nostril, ascending in direction of the conchae (boxes in figure 2 left). The exemplary xy-slices (I-III) show the coronal cross section perpendicular to the main direction of the flow (figure 2 upper part) and the yz-slices (I(z-axis)-III(z-axis)) show the sagittal section, indicated by the white dashed line. The colour-coded velocity magnitudes  $|V|$  reach up to 0.3 m/s. The vector field shows a main flow in direction of the upper region of the main nasal cavities. However, this changes, visible at the yz-slices, the closer the RoI is to the conchae. Additionally, also in respect to the comparison of repeating cycles, unsteady peaks in the velocity magnitudes are visible. The described project provides high-spatial resolved flow data in several RoIs of a test person's nasopharynx considering different breathing cycle states. The combination with the micro-CT scan of the geometry will provide an experimental validation base for numerical investigations. The highly complex geometry combined with a cyclic flow requires investigation of PIV-parameters, like PIV-dt and seeding strategies, in each RoI. The experimental setup enables a high spatial resolution investigation comprising detailed information of the flow regime in several RoIs in the nasopharynx within different cycle states. Furthermore, the precise time-control of the setup's components combined with repeated measurements provides analyses of unsteady flow phenomena.

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