# Korrelationsvelocimetry zur Messung turbulenter Signale in den menschlichen Atemwegen

## Correlation velocimetry for the measurement of turbulent signals in the human airways

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### Abstract

We want to present proof-of-concept measurements for characterizing turbulent flows within a transparent replica of the upper human airways by means of an adopted Laser-Correlation-Velocimetry (LCV) measurement technique. So far, this measurement technique has only been employed for flow measurements of dense sprays. Our proposed approach utilizes an in-line LED illumination for the velocity determination of internal flows within a refractive index matched model. The light intensity of the illuminated volume is captured by two photo-diodes. When a tracer particle crosses the measurement area, it blocks the light of the LED from reaching the receiving optics and the resulting loss of signal is detectable. By placing the two photo-diodes in flow direction, they detect crossing particles within a finite time delay. This delay is determined using a window-based cross-correlation approach, which can be used to calculate the local flow velocity. In contrast to other 1D measurements like Laser-Doppler-Anemometry (LDA) or Laser-2-Focus (L2F), which rely on a very precise positioning of the laser beams, this yields the advantage of being more robust against local optical distortions. As a proof of the measurement technique's capability and suitability, we present results of an oscillating flow within the trachea of a realistic model of the human upper airways ($Re$ = 3652, $\alpha$ = 2.7) and compare the obtained flow profiles with Particle Image Velocimetry (PIV) data.

### Introduction

Recently, advanced velocity measurement techniques, such as Magnetic Resonance Velocimetry (MRV) (Banko et al. 2015; Banko et al. 2016), 3D-Particle Tracking Velocimetry (3D-PTV) (Janke et al. 2017; Corso et al. 2019) or Tomographic Particle Image Velocimetry (Tomo-PIV) (Hasler and Obrist 2018), have been introduced to the research field of biomedical flows. With these approaches it is possible to capture the whole three-dimensional flow field at once. The disadvantages of the aforementioned methods are their complex measurement set-up, high costs and the need for a large digital storage space. Especially for long measurement series, as they are needed for a statistical analysis of turbulent flows, this can limit the suitability of these modern techniques.

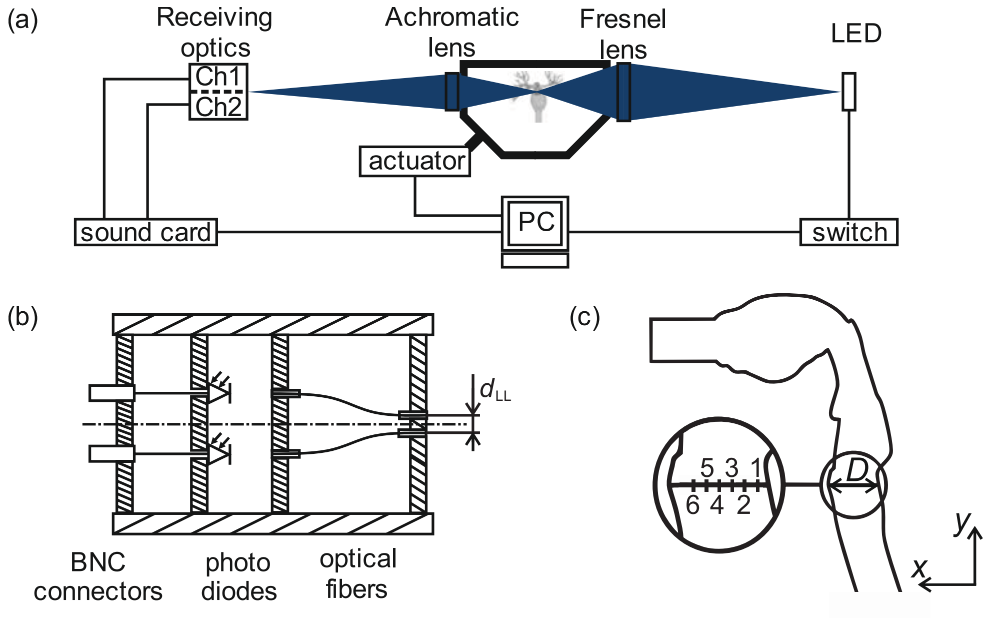


Fig. 1: Measurement set up for the correlation velocimetry measurements (a), cross-section of the receiving optics (b) and the location of the measurement positions (c).

In the past, many studies, covering the characterization of turbulence, utilized point-wise measurement approaches as hot-wire anemometry, laser doppler anemometry (LDA) or laser two focus anemometry (L2F). While these measurement techniques are easily applicable for external aerodynamic flows, it can be complicated to measure the flow velocity within complex geometries. Especially, when a liquid is used as a working fluid or refractive index matched techniques are incorporated, additional media interfaces can strongly disturb the recorded signals. This effect is specifically problematic for L2F and LDA measurements, where it is necessary to precisely align two very small measurement volumes.
Another point-wise laser measurement technique is the Laser Correlation Velocimetry (LCV) (Chaves et al. 1993; Hespel et al. 2012). Instead of relying of two laser beams, this measurement approach places the light source and the receiving photo diodes at an in-line configuration. Therefore, just a single light source illuminates the measurement, which simplifies the set up. Additionally, this may overcome the problems arising from the crossing of several interfaces. But, to the best of our knowledge, no studies have been conducted so far, which test the LCV performance for complex internal flows.
With this work, we want to present a modified correlation velocimetry (CV) technique, which utilizes an in-line LED illumination and test its application for the velocity measurements within a realistic patient-specific, refractive index matched lung model. In order to evaluate the obtained results, a comparison with PIV data is employed.

## Experimental set up

The presented measurements are conducted at our lung flow facility, which has already been presented and described in the past (Janke et al. 2017; Janke et al. 2019). Therefore, just the main key components shall be mentioned, here. The facility incorporates a large tank, in which a model can be submerged. The working fluid is a water-glycerin mixture (43:57 mass ratio, $\rho$ = 1150 kg/m³, $\nu = 8.4 \cdot 10^{-6}$ m²/s) and it is seeded with nearly neutrally-buoyant tracer particles ($d_p$ = 50 µm, $\rho$ = 1060 kg/m³). A linear actuator and a piston-diaphragm pump is used to create the main flow. The measurement section is optically accessible via several windows.

A realistic patient-specific lung model is placed within the tank and investigated for the current studies. The model is based on the SimInhale benchmark geometry Koullapis et al. 2018 and has been introduced by Lizal et al. 2012. Details on the manufacturing of the used model can be found in Janke et al. 2019. The hydraulic equivalent diameter of the trachea is $d_T$ = 16.3 mm. Based on this value and an applied tidal volume of 500 ml and a modeled breathing frequency of 0.15 Hz, the Reynolds number equals to Re = 3652 and the Womersley number to $\alpha = 2.7$.

In order to perform the correlation velocimetry measurements, a light emitting diode ($\lambda$ = 470 nm) is placed in-line with a specifically constructed receiving optics (see Fig. 1 (a)). The light is focused by a Fresnel lens ($f$ = 219 mm) at the center of the model. After passing the model, an achromatic lens ($f$ = 50 mm) images the light onto the receiving optics. All optical components, excluding the Fresnel lens, can be traversed along every axis. In addition, the receiving optics can be rotated around its symmetry line. With the aim of measuring the main flow component, the optical fibers are placed along the y-axis (see.Fig. 1 (c)).

The receiving optics consist of a metal housing, which holds two photo diodes (see Fig. 1 (b)). As their dimensions prohibit a very close positioning, two optical fibers ($d$ = 250 µm) are placed in front of the photo diodes and are connected to the front plate of the housing. The center point distance of the two optical fibers is $d_{LL}$ = 1.32 mm (see Fig. 1 (b)). BNC connectors are attached to the photo diodes to send the signal to an external digital soundcard ($f_s$ = 44,1 kHz).

All measurement runs are synchronized to start at the flow reversal point from expiration to inspiration. This is achieved by sending a TTL signal from the actuator's control unit at the corresponding position, to a switch, which interrupts the circuit of the LED for a short period. The resulting signal change can be clearly identified in the recordings and marks the beginning of the measurement.

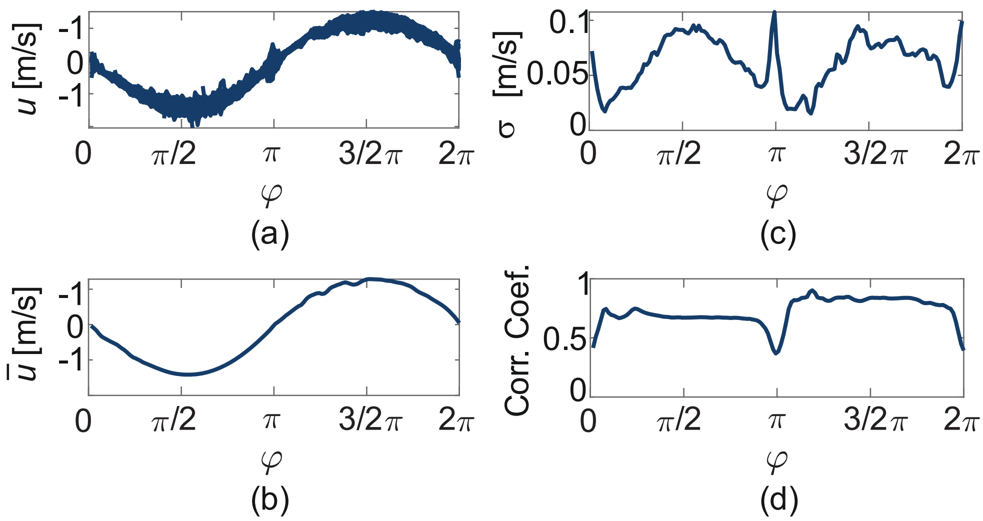


Fig. 2: Exemplary obtained results by the CV measurement. (a) Overlapping velocity signals of all recorded periods, (b) averaged velocity signal, (c) standard deviation of velocity signal, (d) mean correlation coefficient for each phase position.

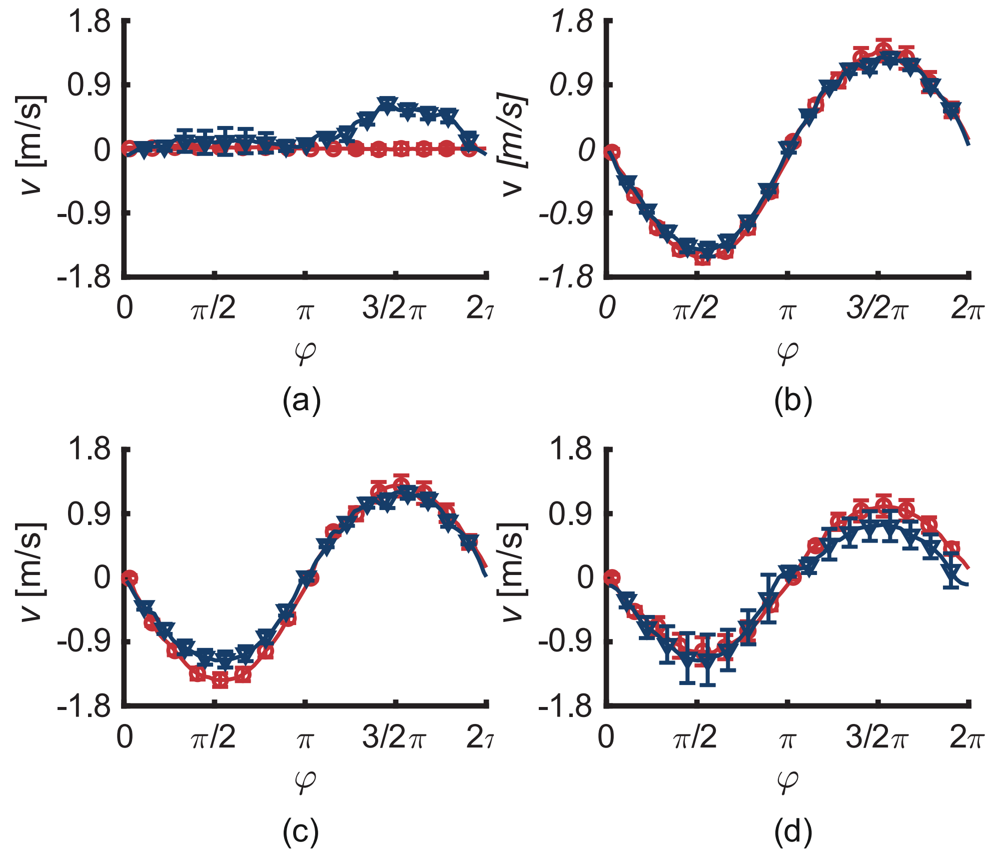


Fig. 3: Comparison of phase-averaged velocity *v* over phase position *j* for CV measurements (**-∇-**, every eight point is plotted) and PIV measurements (**-o-**, every fourth point is plotted). The error bars indicate the standard deviations for all measured periods. (a) Profile position 1 (*x*/*D* = 0.09), (b) Profile position 3 (*x*/*D* = 0.35), (c) Profile position 4 (*x*/*D* = 0.49), (b) Profile position 6 (*x*/*D* = 0.75).

## Correlation velocimetry measurements

The proposed CV method is an imaging technique. This means, that the illuminated measurement volume is projected and magnified ($M$ = 5) onto a defined image plane, in which the receiving optics is positioned. Since the emitted light is captured by two optical fibers with a distance of $d_{LL}$ = 1.32 mm and the magnified diameter of the trachea at the measurement position is 114 mm, it is possible to precisely position the receiving optics at the desired locations.
The signals important for the evaluation and determination of the flow velocity are not created by scattered light of the tracer particles as in L2F or LDA, but by the shadows of the particles as they cross the measurement volume. When both light capturing photo diodes are placed in main flow direction, they record the passing of a particle with a certain time delay d$t$. This delay is determined not by identification of single particle passing events but by a window-based cross-correlation approach. The chosen window size for the evaluation is set to 4096 samples to ensure a sufficient number of crossing particles within the window. An overlap of 50% of the interrogation window size is used to improve the temporal resolution. With these evaluation settings, the breathing curve can be sampled with 143 points per cycle, which corresponds to a measurement frequency of around 21 Hz.
In the here presented measurements, the intensity signals are recorded continuously for 530-540 breathing cycles. After cross-correlating the signals from channel 1 and 2, the whole velocity signal is split into single periods. This is achieved by determining the breathing fre-

quency via a Fast Fourier Transformation (FFT) and a further optimization, based on the minimization of the standard deviations. The deviation between the programmed frequency and the evaluated one is below 0.01 %, which indicates a stable operation of the linear actuator during the measurements.

An exemplary evaluation of the CV measurements is illustrated in Fig. 2. Within this figure, an overlap of all acquired periods is shown (a), from which the phase-averaged velocity signal and its corresponding standard deviation is derived (b) & (c). In addition, the mean values of the correlation coefficient are plotted as well. For most parts, these values are around 0.6 - 0.7. But they fall below 0.5 at the points of flow reversal ($\varphi = 0\pi$ and $\varphi = \pi$). The consequence of this is a rise of the standard deviation, as the flow velocity cannot be reconstructed unambiguously at this phase position. Since the flow does not follow the orientation of the vertical placement of the photo diodes anymore, the cross-correlation does not give a physical meaningful response.

## Results & Discussion

Our first results shall be presented within this section. The PIV data, used as a comparison for the CV measurements, have been reported previously in Janke et al. 2019. Measurements are taken at six positions across a line within the upper trachea as shown in Fig. 1 (c).

The velocity $v$ (y-direction) over the phase position $\varphi$ is plotted in Fig. 3 for the measurement positions 1, 3, 4 and 6 ($x/D$ = 0.09, 0.35, 0.49 and 0.75). All data points represent the phase averaged velocity over all recorded cycles with their corresponding standard deviation as error bars. For positions 3, 4 and 6 we find an overall good agreement of the obtained results with the PIV. Slight underestimations of the velocity magnitude are observable at position 4 during inspiration ($\varphi = 0 - \pi$) and at position 6 during expiration ($\varphi = \pi - 2\pi$). A larger difference occurs during expiration at position 1 ($x/D$ = 0.09). Even more, during inspiration the results suggest a flow direction contrary to the expected main direction. As it is known from the PIV study (Janke et al. 2019), position 1 lies within the recirculation region, created by the laryngeal jet.

When looking at the whole velocity profile at single phase positions (see Fig. 4) an overall good accordance between CV and PIV is observable as well. During inspirational flow, every measured velocity, except for position 1 ($x/D$ = 0.09) and 4 ($x/D$ = 0.49), corresponds to the PIV data within its uncertainty range. At position 1 and 4 the derived velocities tend to be slightly lower in magnitude, than expected from the PIV evaluation.

At the second half of the breathing cycle, an equivalent agreement can be found. But during this flow phase, position 5 ($x/D$ = 0.61) shows the largest deviations. Of all CV measurements this position also indicates the largest uncertainty of the mean calculation but still represents a satisfying result, when taking the PIV velocity profiles as a reference.

Two main reasons for the mismatching positions can be assumed. The first one is the alignment of the receiving optics. As the positioning of the optical fibers was fixed to be along the y-axis but no further studies in varying the rotation have been conducted, there might be a slight deviation between the alignment of the photo-diodes and the main flow direction. As a second point it is to note, that during the PIV studies, the measurement plane has not been perfectly parallel to the middle plane of the lung model. The light sheet was inclined by 2° to cover a larger FOV. This can contribute to a slightly different measurement location and therefore to different measurement results.

Nevertheless, the results suggest a promising performance for the future application of the correlation velocimetry (CV) technique in refractive index matched models.

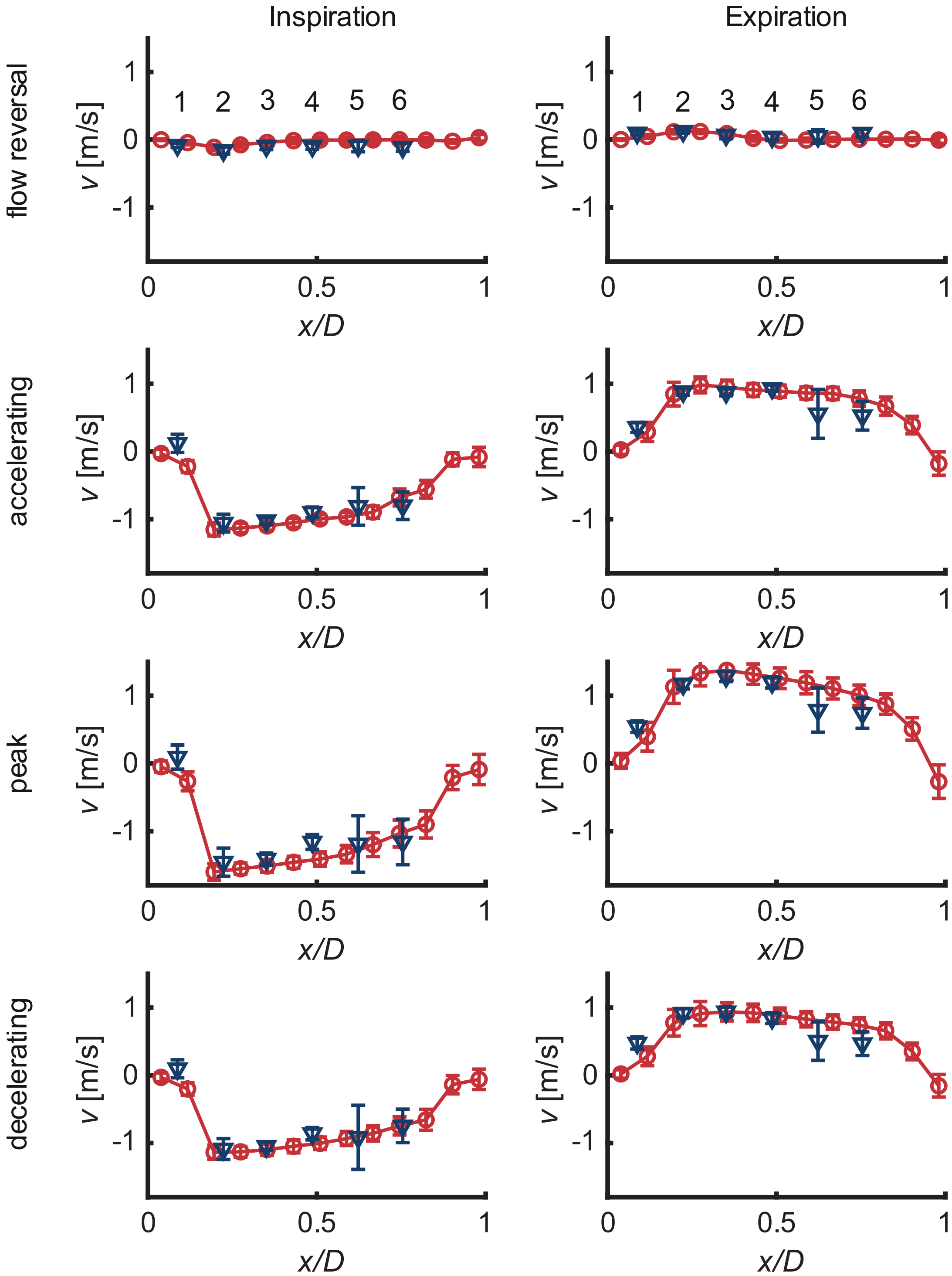

Fig. 4: Comparison of phase-averaged velocity profiles *v* over the trachea diameter *D* for CV measurements (-∇-) and PIV measurements (-o-, every fourth point is plotted). The error bars indicate the standard deviations for all measured periods.


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## Conclusion

Correlation velocimetry measurements with the aim of providing a proof-of-concept study to utilize the measurement technique for the characterization of turbulent internal flows have been perform within a realistic lung replica at oscillatory flow (Re = 3652, $\alpha$ = 2.7).
All in all, our results suggest a promising performance of the Correlation Velocimetry measurement technique even for internal flows with several media interfaces.
Future work will have to cover a more in-depth investigation on error influences and limitations of the technique, an optimization of the seeding density to allow higher measurement frequencies and in addition, modifications of the cross-correlation process are advised to account for changing flow velocities and to improve the overall performance.

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