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Tomographic particle image velocimetry of a water-jet for low volume harvesting of fat tissue for regenerative medicine

Abstract: Particle Image Velocimetry (PIV) measurements of a water-jet for water-assisted liposuction (WAL) are carried out to investigate the distribution of velocity and therefore momentum and acting force on the human subcutaneous fat tissue. These results shall validate CFD simulations and force sensor measurements of the water-jet and support the development of a new WAL device that is able to harvest low volumes of fat tissue for regenerative medicine even gentler than regular WAL devices.

Keywords: water-assisted liposuction; WAL; water-jet; PIV; Tomographic Particle Image Velocimetry

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1 Introduction

The water-assisted liposuction is a well-established and widespread method for gentle human fat tissue harvesting. A pulsating water-jet is injected into the subcutaneous fat tissue to detach clusters of fat and stem cells from the connective tissue and leave the surrounding tissue almost unharmed. The water-jet (saline, adrenalin, lidocaine) is injected through the centre of the cannula (see Figure 1) and reflected over a baffle to form a fan-shaped water-jet [1, 2].

The tissue is aspirated by a vacuum pump through the slotted holes at the side of the cannula (see Figure 1). To allow a permanent aspiration of fat tissue both injection of water and aspiration of fat tissue are conducted simultaneously.

A new WAL device for regenerative medicine with an even gentler water-jet is to develop. The water-jet is therefore investigated using numerical flow simulations (Computational Fluid Dynamics, CFD), experimental Particle Image Velocimetry (PIV) by injecting into water and integral measurement of the acting force of the water-jet using a force sensor by injecting into air (see Figure 2).

The space-resolved results of the PIV measurements can then be compared to the integral results from the force sensor but both results are mainly used to validate the CFD simulations. Only these simulations allow the investigation of the injection of the water-jet into arbitrary fluids that are similar to fat tissue in density and viscosity.

Only the experimental investigations that use the method of Particle Image Velocimetry and their first results shall be described and discussed in this paper.

Particle Image Velocimetry is a laser-optical measurement technique based on particles that are seeded into a fluid and follow its flow. These seeding particles are then illuminated by a laser source and captured by one or more cameras twice in quick succession. The camera pictures are analysed by complex algorithms like image pre-
processing and cross-correlation to calculate a vector field of the velocity [4, 5].

2 Methods

2.1 Test setup

In this investigation an advanced PIV method, the Tomographic Particle Image Velocimetry, is used. At usual Planar PIV and Stereo-PIV a thin light sheet is expanded of the laser beam by a special sheet optics and the positions of the illuminated seeding particles are captured by one or two cameras. In contrast to that at Tomographic PIV a volume optics expands the laser beam to a thick illumination volume that surrounds the nozzle. Three LaVision Imager sCMOS double-frame cameras (LaVision, Göttingen, Germany) that are mounted under different angles capture the positions of the illuminated seeding particles during each of the two illuminations. A volume of the positions of the seeding particles is calculated from the three recordings of the three sCMOS cameras for both recordings in quick succession using special tomographic reconstruction algorithms [6]. Subsequently the three-dimensional velocity vectors in the illumination volume are calculated from the two reconstructed seeding particle volumes using cross-correlation.

The laser source used in this setup is a nano s piv Nd:YAG double pulse laser (Litron Lasers, Rugby, UK) with a wave length of 532 nm, a pulse energy of 50 mJ and a maximum repetition rate of 20 Hz [7]. Usually a special volume optics is necessary for Tomographic PIV [8] but was not available for these first investigations. Instead an existing LaVision Planar PIV/Stereo PIV light sheet optics [9] was used by defocussing the expanded light sheet to generate a divergent 4 mm thick illumination volume.

Since the timing of injection, illumination and capturing is very important all these devices have to be synchronised. To time nozzle, laser and cameras on each other the WAL device, the laser and the cameras are connected to a LaVision Programmable Timing Unit (PTU). When the pump of the WAL device is activated by the user to inject through the nozzle the signal is tapped and passed into the PTU. The PTU then triggers both the laser to illuminate the seeding particles and the cameras to capture the position of the seeding particles.

2.3 Calibration

To obtain results of a high quality special attention has to be paid to the calibration of the three cameras. Since only an illumination volume with a thickness of up to 4 mm is available for this investigation it is only necessary to perform a single calibration that uses the two layers of the 3D calibration plate (see Figure 4).

3 Results

The results of this study allow a first insight into the velocity distribution within the water jet. Also the form of the water-jet can be reconstructed plotting the isosurfaces of velocity.
Figure 5 shows a time series of vectors and isolines of velocity in the symmetry plane \( y = 2 \) mm of the 4 mm illumination volume plus the three-dimensional isosurfaces of the velocity within the entire 4 mm illumination volume in the water basin around the WAL nozzle.

The upper left image in Figure 5 shows the velocity distribution just after the start of the injection of the WAL water-jet at 0.05 s. Before the injection the water in the basin rests, the velocity is zero. With the water-jet entering the basin it displaces more and more resting water while transferring momentum to that surrounding water. This surrounding water is accelerated and starts to move. At 0.15 s and 0.2 s the velocity vectors at first point away from the water-jet and then even point towards it. This indicates that there are vortices next to the mainstream of the water-jet. Turbulence is created.

The spatial extent of the water-jet is visualised by plotting different isosurfaces of the velocity. Isosurfaces for 0.1 m/s (cyan), 0.6 m/s (yellow), 0.8 m/s (magenta) and 1.0 m/s (red) are shown in Figure 5.

While the water-jet is still very small at 0.05 s, it increases in size constantly. More resting water is displaced by injected water with its higher velocity. The volume covered by the isosurfaces grows during the time-series. The 0.1 m/s isosurface is the outermost isosurface of the four and therefore a good indication for the spatial extent of the water-jet.

The more the water-jet enters the basin the higher velocities inside the water-jet can be measured. The yellow isosurface that represents 0.6 m/s is already recognizable inside the water-jet at 0.05 s. The velocity inside the water-jet at 0.1 s already reached 0.8 m/s which is indicated by the magenta isosurface. At 0.2 s the velocity reaches 1.0 m/s in the very tail of the water-jet.

It is also to mention how the water-jet is ‘cut’ by the illumination volume. While at 0.05 s the cyan isosurface is still surrounding the water-jet it opens up more and more over time. At 0.1 s and 0.15 s there is still a band formed by the cyan isosurface.

Also the outer isosurfaces fragment more and more over time (see Figure 5 in the lower right image). This occurs due to the breakup of the water-jet and the collapse of the bigger vortices next to the water-jet. Smaller regions of the same velocity and therefore more fragmented isosurfaces are the result.

The fragmentation of the outer isosurfaces also occurs due to the thin illumination volume of 4 mm which only allows the observation of a 4 mm slice of the fan-shaped water-jet. In the boundary region of the illumination volume seeding particles are once illuminated and once not so that an incorrect cross-correlation and therefore an incorrect calculation of the velocity vectors results.
4 Conclusion and outlook

Particle Image Velocimetry measurements are carried out to support the development of a new WAL device for regenerative medicine. The PIV measurements are to compare to force sensor measurements and to validate CFD simulations. The WAL nozzle is placed in a transparent water basin and injects water seeded with glass hollow spheres. To observe a volume instead of a thin sheet of the water-jet an advanced PIV method, the Tomographic Particle Image Velocimetry, is used.

The first Tomographic PIV measurements show promising results. During the beginning of the injection form and extent of the entire water-jet is observable within the 4 mm illumination volume. While the injection proceeds more momentum is transferred from the injected water to the surrounding water in the basin. Vortices develop from the mean flow and it is harder to observe the fluid flow especially at the boundary of the illumination volume.

Therefore it is desirable to prevent the cutting-off of the water-jet and enlighten it entirely. So the light sheet optics is to replace with a new volume optics that is able to expand a cube-shaped illumination volume of 20 mm around the nozzle.

For illumination volumes thicker than 4 mm the calibration process will be more complex. Instead of one calibration where the 4 mm illumination volume matches the two levels of the 3D calibration plate coincidentally several manual calibration processes at different parallel planes within the illumination volume each using the two levels of the 3D calibration plate have to be performed.

To allow a calibration with several parallel planes the 3D calibration plate has to be moved in y-direction using a linear table that guarantees accuracy in movement. This linear table is mounted on a calibration portal that allows pulling up the calibration plate after the calibration without destroying this calibration by jiggling at the PIV setup (see Figure 6).

When all this is accomplished useful measurements of the WAL injectors can be conducted to compare different nozzles, flow rates or pressure levels.

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Figure 6: Concept of the new calibration portal for Tomographic PIV that allows the calibration of a 20 mm illumination volume.

Author’s Statement
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References