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Fabrication of a flexible stenosis phantom for flow measurements using additive manufacturing

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Abstract: Obstructive sleep apnea (OSA) is a common sleep disorder caused by the collapse of the upper airway during sleep due to a shift of soft tissues. To further optimise the treatment, one needs a better understanding of the patient-specific causes of OSA. For this purpose, flow measurements shall be executed with flexible phantoms. A first measurement campaign was carried out with a flexible stenosis phantom. To build this phantom a multipiece water-soluble casting mold was fabricated with additive manufacturing and used to cast the phantom with silicone. The quality of the phantom was tested with regard to the wall thickness using CT measurements.

I. Introduction

Obstructive sleep apnea (OSA) is a common sleep disorder caused by the repetitive complete or partial obstruction of the upper airway due to a shift of soft tissues. For a better understanding of airflow characteristics and tissue conditions that lead to the obstruction, numerical simulations can be used to calculate flow patterns and deformation behaviour. To ensure reliability of the simulations, a validation of the results is highly relevant. For this purpose, flow measurements shall be carried out with flexible phantoms. Even though in OSA tissue deformation is a key mechanism, most studies use solid phantoms for experimentation and validation [1, 2]. There are just very few studies in OSA research that use flexible phantoms, to examine deformation behaviour [3]. The complex anatomy of a human airway is simplified to a constricted, circular pipe, called stenosis phantom in the following. The phantom properties were chosen according to Geoghegan [4], who used a stenosis geometry to study flow behavior of blood. The stenosis phantom is a silicone cast. The water-soluble casting mold was made with additive manufacturing techniques. Flow measurements were carried out with steady flow using 2D phase contrast magnetic resonance imaging (PC-MRI). As result a 3D volume of a flow field with velocities in axial direction was obtained.

II. Material and methods

A casted flexible flow phantom of a stenosis was made of silicone (Sylgard 184 Silicone Elastomere, Dow Corning, Midland, Michigan, USA). In Fig. 1 the construction drawing of the phantom is depicted to visualise the phantom geometry. The inner diameter of the phantom is 20 mm with a wall thickness of 1.3 mm. The constricted part is cosine shaped, axisymmetric, 40 mm in length and has a diameter reduction of 50 % in the most constricted area. A 3D printer (Ultimaker 2, Ultimaker, Geldermalsen, Netherlands) was used to manufacture a casting mold. The Ultimaker 2 uses fused deposition modeling with a printing layer thickness of 0.1 mm and is capable to switch between two printing materials.

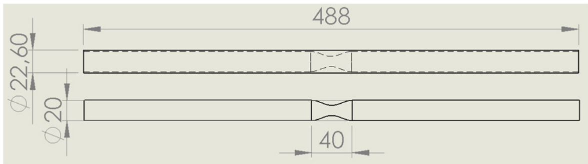

Figure 1: Construction drawing of the stenosis phantom in mm.

Usually this feature is used to apply support structures made of a water-soluble polyvinyl alcohol (Ultimaker PVA, Ultimaker, Geldermalsen, Netherlands) to the printed object. For the purpose of fabricating the stenosis casting mold, solely water-soluble PVA was used. The casting mold consists of an outer part and an inner part. Due to the restricted size of the build volume of the Ultimaker, each part needed to be separated into three intermateable pieces, shown in Fig. 2.

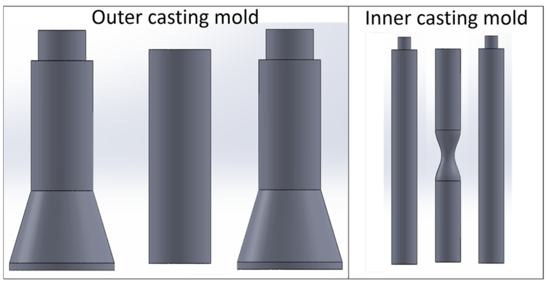

Figure 2: Outer (left) and inner casting mold (right) separated into three intermateable pieces respectively.

For postprocessing of the printed parts the surface was coated with polyvinyl acetate glue (PVA glue) to seal the pores. To be able to assemble the three pieces of each casting mold, the joints needed to be grinded and finally bonded together with PVA glue. For the casting process, the mold was fixed together and closed with two end pieces, made of poly(methyl methacrylate) (PMMA). The final mold, shown in Fig. 3, was then used to cast the stenosis phantom with Sylgard 184, a silicone with a Young's modulus of 1.2×10^6 N m^{-2}. After the silicone was cured, one could remove the casting mold by setting it in a warm water bath for a few days.

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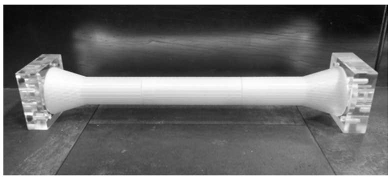

Figure 3: Assembled casting mold fixed together with two end pieces.

As a measure of quality the actual wall thickness provided by CT imaging was used. A transversal cut view of the CT image is depicted in Fig. 4. For the imaging a tube voltage of 120 kVp was used with a voxel size of 0.4 x 0.4 x 0.6 mm3. The wall thickness was measured with a threshold technique at seven different positions along the phantom with 0 mm, ±20 mm, ±40 mm and ± 60 mm distance to the center of the constricted area. At each position four circularly arranged measurement points were considered, shown in Fig. 5. To study the flow behaviour of the phantom a 2D PC-MRI measurement was performed with a 3 T MR system (Ingenia, Philips, Amsterdam, Netherlands) (MR parameters: TR = 10 ms, TE = 6 ms, flip angle = 7°, pixel spacing = 0.89 x 0.89 mm2, slice thickness = 1 mm). An MR compatible flow pump (CadioFlow-5000MR, Shelley Medical Imaging Technologies, London, Ontario Canada) generated steady flow with a flow velocity of 29 cm s-1. This corresponds to a Reynolds number (Re), a parameter to ensure dynamic similarity, of 1000, which is, according to [5], in the range of lighter breath in the trachea. The flow velocity is recorded through a plane perpendicular to the flow direction. As recommended for the pump, an MRI-visible flow medium, a glycerol/water mixture of 55 % glycerol mass fraction, was used. The transmural pressure, which is defined as the pressure difference between inner pressure and outer pressure, was set to 8 kPa. Further information about the phantom fabrication and the flow measurement can be found in [6].

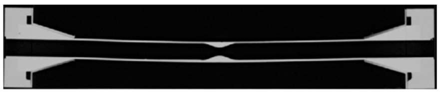

Figure 4: CT image for quality control of the final phantom.

III. Results and discussion

The mean measured wall thickness of the stenosis phantom is 1.7 mm ± 0.4 mm. At the center of the constriction the wall thickness is 6.6 mm ± 0.4 mm. In average the wall thickness is increased by 0.4 mm from the planned wall thickness of 1. 3 mm outside of the constriction and 6.3 mm at the center of constriction. Nevertheless, the deviation is still in the range of the image resolution with 0.4 x 0.4 mm^2. Also, a slight asymmetry of the wall was observed, exemplary shown in one slice in Fig. 5. A probable cause of the asymmetric wall thickness might be a slight lateral shift of the inner part of the casting mold in relation to the outer part. For future trials an even more accurate method to adjust the parts of the casting mold should be considered. All in all the deviation of the wall thickness from the desired phantom geometries is in the sub-millimeter range, meaning that in general a highly accurate phantom fabrication is possible with the applied manufacturing method. For this specific phantom though a deviation of the wall thickness of 0.4 mm, means a difference of 42 %. Therefore, further optimising of the manufacturing method is needed.

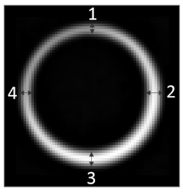

Figure 5: Slice of CT image of the phantom to measure wall thickness at four points respectively. A slight asymmetry can be observed.

The result of the velocity measurement with 2D PC-MRI is shown in Fig. 6. As the flow passes the stenosis the velocity increases significantly. Behind the stenosis, flow separation can be observed and a jet is formed. Lateral to the jet, negative flow velocities occur. This is due to vortexes and turbulences that develop downstream of the stenosis and lead to jet dissipation.

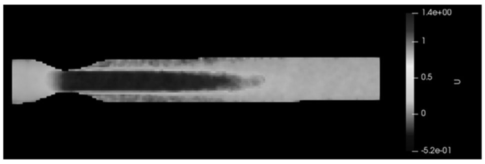

Figure 6: 2D flow sensitive MRI measurement to obtain flow velocities (in m/s).

IV. Conclusions

In this study, a flexible stenosis phantom was fabricated from Sylgard 184 using additive manufacturing and a casting method. Even though the fabricated phantom had a deviation of the desired wall thickness from the planned phantom geometries in the sub-millimeter range, the quality of the phantom was assessed as very high. A first 2D PC-MRI flow measurement was carried out successfully. This work shows that flexible phantom production for 2D PC-MRI is possible with the use of additive manufacturing. For future studies this technique can be applied to fabricate flexible pharynx phantoms and thus to enable complex MRI flow measurements in OSA research.

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