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Micro Particle-Image-Velocimetry for characterization of a micro-mechanical valve in a glaucoma implant

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Abstract

Controlled reduction of intraocular pressure is a main issue in treatment of glaucoma. A novel approach of glaucoma implant is based on a silicone microstent draining the aqueous humor from the anterior chamber of the eye into the suprachoroidal space. The paper presents micro particle-image velocimetry as a method to characterize the fluid-mechanical function of the micromechanical valve.
The current field around the valve region was measured quantitatively. The flow velocity ranged from 1E-6 to 2.5E-2 m/s depending on pressure difference. The valve opening pressure was Δp=4 mmHg indicated by an elevation of flow velocity by almost two orders of magnitude at this pressure difference. Further improvements of µPIV method will be a powerful tool for development and in particular for investigation of flow phenomena at pressure differences around the opening pressure as well as for new valve designs.

1 Introduction

Glaucoma is a serious disease of optic nerve leading to irreversible blindness if not treated. Increased intraocular pressure (IOP) is a major risk factor. So the main purpose of any glaucoma treatment is to reduce IOP to a pressure which prevents loss of retina ganglion cells and thus progression of visual field loss [1,2]. Currently, the widely accepted concept is pharmacological reduction of IOP followed by laser methods or surgical procedures like trabeculectomy and deep sclerectomy, or finally by glaucoma implants. A novel approach is based on a glaucoma microstent draining the aqueous humor from the anterior chamber of the eye into the suprachoroidal space [3] (figure 1).

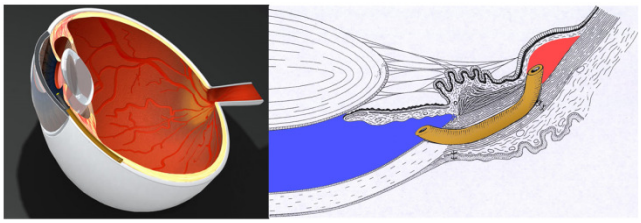

Figure 1 Location of the microstent in the human eye for drainage into the suprachoroidal space

To overcome severe complications of post-operative hypotony a microstent was developed containing a micro-mechanical valve for automatic IOP regulation [3]. This paper presents the application of Micro Particle Image Velocimetry (µPIV) for fluid-mechanical characterization of the valve.

2 Methods

Microstent prototypes made of silicone (Silastic Rx50, Dow Corning, USA) were manufactured using femtosecond laser ablation (figure 2). The valve flap was designed to open at increasing outer pressure and thus enabling additional drainage of aqueous humor. The design was engineered by Finite Element Analysis (FEA) considering mechanical material properties [4]. Figure 3 demonstrates the operating principle showing the valve in an open state.
For current field measurements the device was placed at a diaphragm dividing the special test chamber [5] into two parts. The inflow region is located in the chamber part with the higher pressure (intraocular pressure p_1) while the chamber section with lower pressure (p_2) contains the outflow region of the microstent. The optical observation and measurement of flow velocities is possible in the marked field of view (figure 3). The current field at the valve of the stent is measured for pressure differences in the range of 1 mmHg $\leq \Delta p \leq$ 16 mmHg.

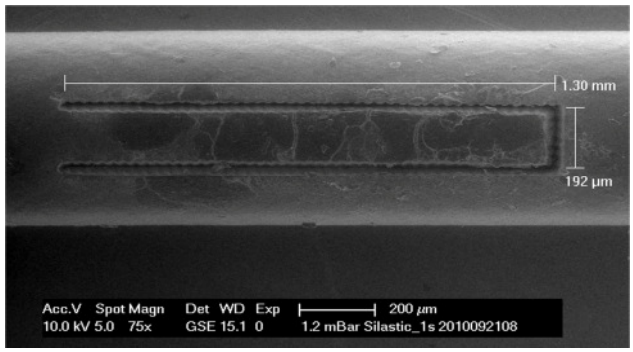

Figure 2 Inflow region of the silicone microstent with laser-cut valve flap (SEM, 75x)

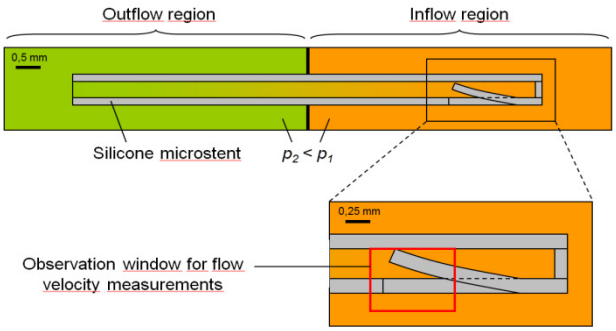

Figure 3 Scheme of microstent with marked valve area as investigated by µPIV

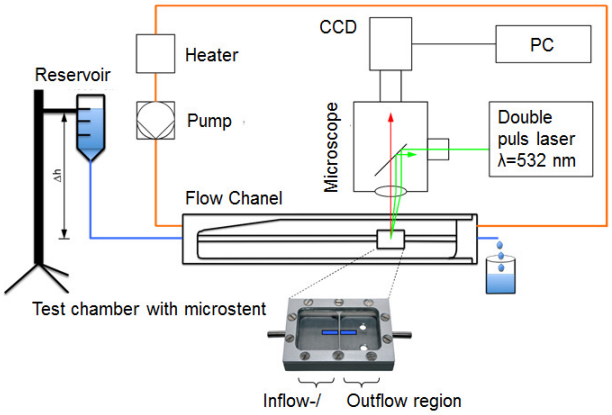

Figure 4 Setup for µPIV investigations of the microstent

The fluid-mechanical characterization of the valve used an adapted µPIV setup (figure 4) with a 532 nm Nd:YAG-laser (Solo III, New Wave Research, USA) [6,7].
The refractivity of the test fluid (ultrapure water with 1.5 µm rhodamine dyed tracer particles, sicastar-redF, micromod, Germany) was matched to silicone by potassium thiocyanate [6,7].

3 Results

The current field outside the microstent was measured. The velocity vector field as measured at three definite pressure differences is shown in figures 5a to 5c. The flow velocity ranged from 1E-6 to 2.5E-2 m/s depending on pressure difference.
The valve opening pressure was Δp=4 mmHg indicated by an elevation of flow velocity by almost two orders of magnitude at this pressure difference (figure 6).
The flow rates inside the microstent failed to measure due to accumulation of tracer particles on the implant surface (figure 7).
These particles did not move but decreased the image contrast in the course of the measurements in a degree that µPIV analysis could not provide valid flow vector data.

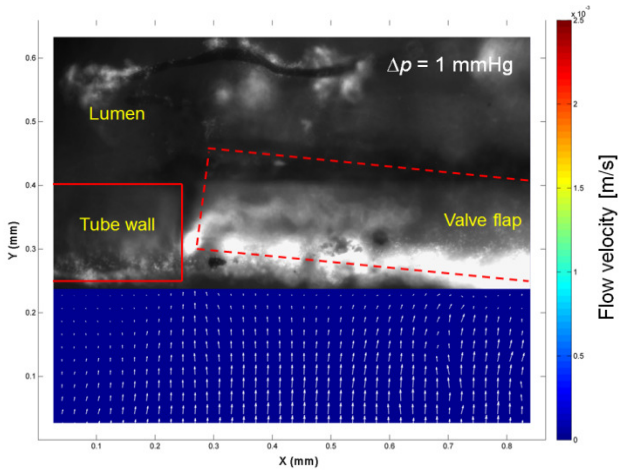

Figure 5a Current field at a valve pressure difference of 1 mmHg

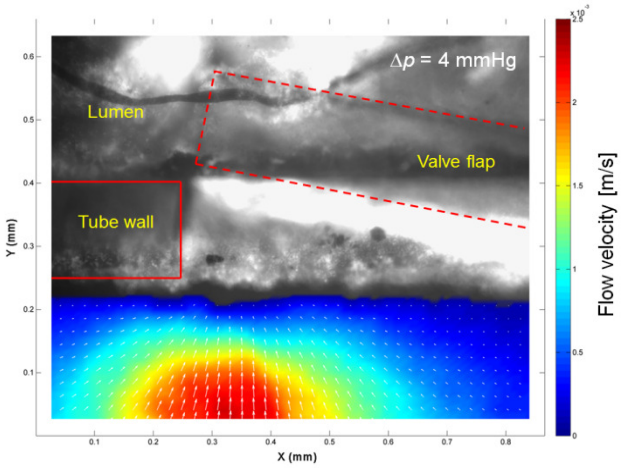

Figure 5b Current field at a valve pressure difference of 4 mmHg

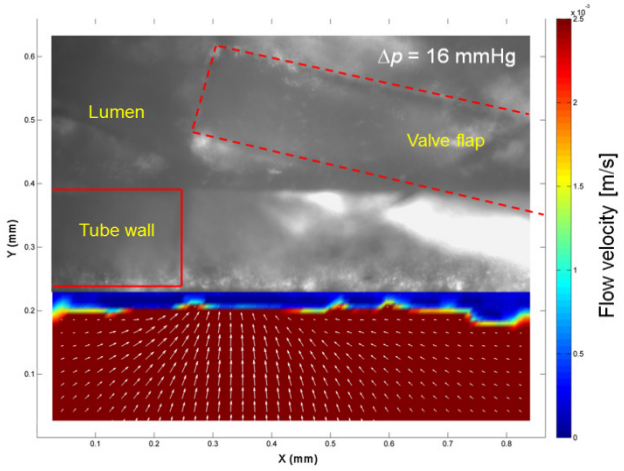

Figure 5c Current field at a valve pressure difference of 16 mmHg, flow within the valve and tube was not measureable (see text)

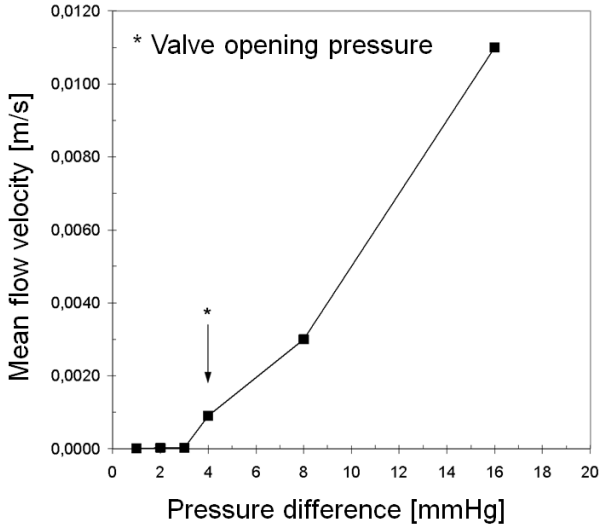

Figure 6 Increase of mean flow velocity at pressure difference of 4 mmHg (identified valve opening pressure)

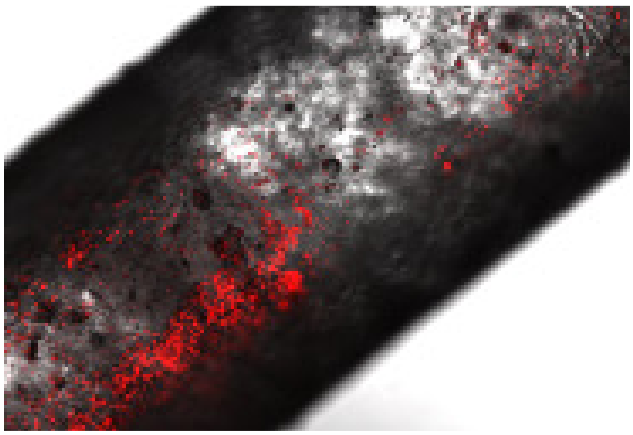

Figure 7 Accumulation of tracer particles (red) inside the microstent shown by fluorescence microscopy

4 Conclusion

Experimental µPIV analysis is suitable for characterization of micro-mechanical valves in glaucoma implants. Compared to detection of valve opening pressure by volumetric flow rate and pressure difference, there is a good correlation (figure 7). A quantitative comparison of mean flow velocity and volume flow based on the presented µPIV measurements is not possible because the measurement of flow velocity was performed only in one plane (x,y). Due to the geometry of the valve, symmetry can be assumed relative to this plane but no further assumption for the current field will be valid. The order of measured flow velocities however is plausible. It can roughly be estimated by comparing i.e. the theoretical flow rate at a given pressure difference with the measured mean flow rate making some assumptions for the dimension of the current fields within the tube and outside.

The valve opening pressure of the investigated microstent is an important functional parameter for the intended application in treatment of glaucoma. The pressure difference between inflow and outflow region depends on the physiological situation of the eye compartments which are connected by the drainage device. In case of drainage into the suprachoroidal space a pressure difference of 2 – 3 mmHg is expected in healthy human eyes [8]. Thus an increased intraocular pressure is indicated by a pressure difference of more than 3 mmHg. In this case the valve would open and thus permitting aqueous humour flow which lowers the IOP. The measured opening pressure meets exactly the intended function of the microstent valve [3,4].

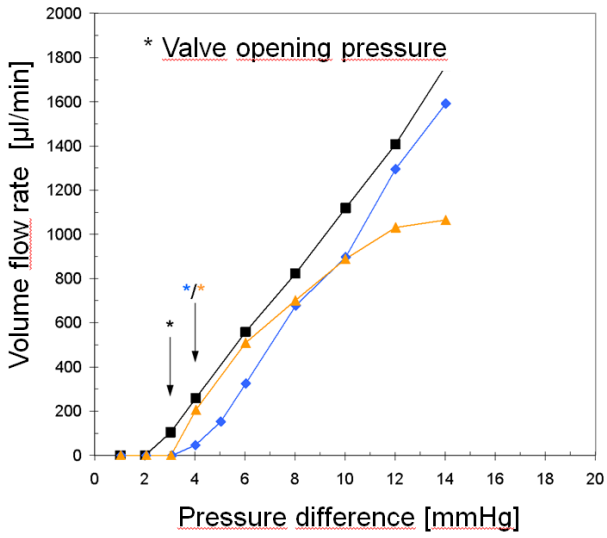

Figure 8 Volume flow rate for of 3 silicon microstent devices (measured by [9])

Improved adaptation of the refractive index of the test fluid is required as well as reduction of particle accumulation on surfaces within the field of investigation. This might be achieved by future hydrophilic or hydrophobic coating of the microstent surface including the inner lumen.

Analysis of glaucoma implants using µPIV will provide qualitative and quantitative information about current fields and will be a powerful tool for development and evaluation of micro-mechanical valves. In particular, flow phenomena at pressure differences in the region of the opening pressure as well as new valve designs will be investigated in future trials.

5 Acknowledgement

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