Comparison of fluid flow between bimanual and coaxial phacoemulsification using computational fluid dynamics

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Research Article

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Abstract

Background: To describe the fluid flow in the chamber of the eye during bimanual and coaxial phacoemulsification using computational fluid dynamics.

Methods: Based on the human eye, a computerized eye model was developed. The fluid flow was modeled using the Navier–Stokes formula, turbulence modeling, and Boolean operations numerically. Several parameters of the flow field were evaluated and compared for both phacoemulsification methods.

Results: Bimanual cataract surgery produced better followability than coaxial cataract surgery. However, bimanual cataract surgery increased the probability of posterior capsule fluctuation and chamber collapse.

Conclusions: Bimanual phacoemulsification improves followability; however, it also increases the probability of posterior capsule rupture and chamber collapse. These findings suggest that there are both advantages and disadvantages to consider when using bimanual phacoemulsification.

Keywords: Bimanual phacoemulsification; Coaxial phacoemulsification; Computational fluid dynamics; Followability; Posterior capsule rupture; Chamber collapse.

Introduction

Cataract surgery is one of the most common surgical procedures. In 1965, phacoemulsification continues to be used today, primarily using the coaxial technique. The cataract surgery has always been moving toward reducing the incision size. In an effort to reduce the size of the incision, Shearing et al. reported a phacoemulsification procedure called bimanual microincision cataract surgery(BMICS) that requires the separation of irrigation and aspiration using two different hand pieces.[1] Several studies have reported the advantages and disadvantages of BMICS.[2-8]

The separation of inflow and outflow has some unique advantages that enhance surgical control during cataract surgery, increase the followability of nuclear fragments[9] and may also be used to protect the posterior capsule. However, the reduced irrigation leads to anterior chamber instability.[10, 11] In recent years, computational fluid dynamics has been widely used for modeling the flow of fluids in complex configurations and has been developed enough to stimulate the complex fluid flow that occurs during phacoemulsification procedure.

The purpose of this study was to analyze the fluid flow in the anterior chamber and the lens cavity using computational fluid dynamics for both BMICS and coaxial microincision cataract surgery(CMICS). The analysis of these factors will confirm whether the followability of nuclear fragments canbe increased by BMICS, whether separated irrigation streams canbe used to protect the posterior capsule, and whether anterior chamber instability canbe aggravated by BMICS.

Methods

The computational eye model used in this study is similar to the typical human eye. Figure1 illustrates the schematics of the computational eye model that includes the anterior chamber and lens cavity. A previous study has reported the normal range of the anterior chamber depth is between 2.5 mm and 3.5 mm.[12] In addition, Considering these values that reported by Adler, the distance from the corneal endothelial surface to the posterior capsule of the lens was assumed to be 7.91 mm in our model.[13, 14] The corneal surface curvature was assumed to have a radius of 7.6mm, and the lens capsule was assumed to be composed of segments of spheres with different radii. All walls were assumed to be rigid. A no-slip velocity condition was imposed. We operated under the assumption that the inside of the lens capsule was completely aspirated. In numerical simulations, both bimanual and coaxial microsurgery cannulas were included. Table 1 shows the sizes of the various cannulas used in this study. Figure 2 shows 3-dimensional views of the models used in BMICS and CMICS including the shape of the cannulas. Table 1 shows sizes of cannulas for the simulation of BMICS and CMICS.

In the BMICS, we assumed that the aspiration cannula and irrigation cannula are inserted 5.6 mm and 3.0 mm, respectively, from the corneal posterior surface. This is because many surgeons place the aspiration cannula tip deep into the anterior chamber to improve the holdability of nuclear fragments and place the irrigation cannula superficially to facilitate chopping.

The irrigation cannula was assumed to be connected to an elevated bottle of BSS. The inlet pressure was set to a 100 cm height of the BSS. The density of the BSS was set to 1.01 g/ml, and its viscosity was set to 0.7 centistokes. The inflow from ciliary body secretion, outflow from the trabecular meshwork, and leaking in the incision sites were ignored in our simulations.

Reynolds-averaged Navier–Stokes, continuity, and transport equations were used to model the motion of an incompressible fluid placed within a turbulent flow regime. The turbulence kinetic energy k and turbulence dissipation energy e were applied to the turbulence model. To study the turbulence, the low Reynolds k-e turbulence model was used for the posterior chamber. The commercial FLUENT software(Fluent, Inc. NY) was used to solve the governing equations using an unstructured grid with tetrahedral cells. The GAMBIT software was used for grid generation, and a grid sensitivity study was performed for different cases. Overall, 2,324,704cells were generated to solve the mesh-independent governing equations for the bimanual and coaxial models. Numerical simulations were performed with several irrigation flow rates and different methods of phacoemulsification. The turbulence kinetic energy was evaluated at the posterior capsule surface for both types of cataract surgeries. As the flow rate increased, the change of predicted variations in the anterior chamber pressure was calculated. The critical flow rate at which the anterior chamber pressure would be less than the ambient atmospheric pressure was also calculated.

Results

Figure 3 shows the pressure contours for the anterior chamber and lens cavity, pressure contours around the entrance of the outlet cannula, and velocity vector in BMICS for a flow rate of 18 ml/min. Outside the cannula, the pressure was 0.707 Pascal. Inside the cannula, the pressure was 0.195 Pascal. Figures 4 shows the metric values for the bimanual cannula for flow rates of 23 ml/min and 28 ml/min. For a flow rate of 23 ml/min, the pressure outside the cannula was 0.018 Pascal and that inside the cannula was −1.49 Pascal. For a flow rate of 28 ml/min the pressure outside the cannula was −0.271 Pascal and that inside the cannula was −2.49 Pascal.

Figure 5 shows the pressure contours for the anterior chamber and lens cavity, pressure contours around the entrance of the outlet cannula, and velocity vector in CMICS for a flow rate of 18 ml/min. Outside the cannula, the pressure was 0.502 Pascal, and inside the cannula, it was 0.201 Pascal. Figures 6 shows the metric values for the coaxial cannula for flow rates of 23 ml/min and 28 ml/min. For a flow rate of 23 ml/min the pressure outside the cannula was −0.384 Pascal and that inside the cannula was −1.65 Pascal. Finally, for a flow rate of 28 ml/min, the pressure outside the cannula was 0.488 Pascal and that inside the cannula was −1.87 Pascal.

For a flow rate of 18 ml/min, the absolute difference between the pressures outside and inside the cannula was 0.517 Pascal for the bimanual cannula and 0.301 Pascal for the coaxial cannula. For a flow rate of 23 ml/min, the absolute difference between the outside and inside cannula pressures was 1.509 Pascal for the bimanual cannula and 1.266 Pascal for the coaxial cannula. For a flow rate of 28 ml/min, the absolute difference between the outside and inside cannula pressures was 2.219 Pascal for the bimanual cannula and 1.382 Pascal for the coaxial cannula (Table2).

The turbulence kinetic energy of the posterior capsule surface was calculated. For a flow rate of 18 ml/min, the difference between the maximum and minimum turbulence kinetic energies of the posterior capsule was 0.299 m^2/s^2 for the bimanual cannulaand 0.199 m^2/s^2 for the coaxial cannula. For a flow rate of 23 ml/min, the difference between the maximum and minimum turbulence kinetic energies of the posterior capsule was 0.199 m^2/s^2 for the bimanual cannula and 0.149 m^2/s^2 for the coaxial cannula. Finally, for a flow rate of 28 ml/min, the difference between the maximum and minimum turbulence kinetic energies of the posterior capsule was 0.149 m^2/s^2 for the bimanual cannula and 0.099 m^2/s^2 for the coaxial cannula (Table3).

Figure 7 shows that the anterior chamber pressure decreases linearly with an increase in the volume flow rate. However, below a critical flow rate, the anterior chamber pressure would be less than the ambient atmospheric pressure and would result in anterior chamber collapse. The critical flow rate in bimanual microincision cataract surgery was 23.148 cc/min, which produced an anterior chamber pressure of 0 Pascal. The critical flow rate in CMICS was 29.419 cc/min, which produced an anterior chamber pressure of 0 Pascal.

Discussion

Computational fluid dynamics is a sub-discipline of fluid mechanics that deals with fluid flow and allows for the simulation of complex fluid systems. It has been applied to various biomedical systems, such as those involved in heart pumping,[15] cardiac valve design,[16] blood flow analysis,[17] vessel graft evaluation,[18] nose or sinus flow analysis,[19] and lung airflow analysis.[20] The separation of inflow and outflow in BMICS allows for smaller incision sizes, which in turn reduces the risk of surgically induced astigmatism, improves intraoperative visibility, and reduces the risk of endophthalmitis. The separation of inflow and outflow also increases the followability of nuclear fragments[9] and flexibility of the two incisions. However, the main disadvantage of BMICS is an increase in anterior chamber instability[10] that results from the limited irrigation. In the present study, we used computational fluid dynamics to further compare the advantages and disadvantages of BMICS and CMICS. Variables of interest included the flow velocity, pressure distribution of the anterior and posterior chambers, turbulence intensity, stability of the posterior capsule, and predicted anterior chamber pressure; all variables were investigated using different flow rates of the irrigating solution. We were particularly interested in measuring the followability of nuclear fragments, posterior capsule fluctuation and the anterior chamber instability during BMICS.

Figures 3, 4 show the pressure contours around the bimanual cannula outlet for flow rates of 18, 23, and 28 ml/min, respectively. For these flow rates during BMICS, the pressure differences between the outside and inside of the cannula were 0.512 Pascal, 1.509 Pascal, and 2.219 Pascal, respectively. For these same flow rates during CMICS, the pressure differences between the outside and inside of the cannula were 0.301 Pascal, 1.266 Pascal, and 2.219 Pascal, respectively (Figures 5,6; Table 2). For both types of cataract surgeries, the absolute pressure difference between the outside and inside of the cannula increased as the flow rate increased. At the same flow rate, the pressure difference between the outside and inside of the cannula was always larger in BMICS than in CMICS. This pressure difference between the outside and inside of the cannula is the measure of followability. The larger pressure difference between the outside and inside of the cannula has higher followability of nuclear fragments. Therefore, in our simulation, the followability measured during BMICS was found to be greater than that measured during CMICS. These results are consistent with those of previous reports. Agarwal et al. also reported that the separation of irrigation and aspiration increased the followability of nuclear fragments.[2] The inflow and outflow of fluids occurred at the same spot of cannula simultaneously in CMICS. However, in the BMICS, the nucleus is not pushed away by the infusion fluid flow. And there are no published evidence reporting such a result. Overall, based on our simulation, bimanual cataract surgery was shown to be superior in terms of followability.

One of the worst complications that can occur during cataract surgery procedures is posterior capsule rupture(PCR). To compare the probability of PCR occurring in either type of microincision cataract surgery, we evaluated the turbulence intensity measured by turbulence kinetic energy and the pressure gradient of the posterior capsule. The turbulence kinetic energy means the intensity of the fluctuation and unsteadiness of the flow velocity. The turbulence kinetic energy measured during BMICS was found to be higher than that during CMICS(Table3). As the flow rate increased, the turbulence kinetic energy for both cataract surgeries decreased. The pressure gradient of the posterior capsule in BMICS was more diffuse than that observed in CMICS(Figures 3–6). In the BMICS, the difference in the posterior capsule pressure gradient decreased as the flow rate increased. In BMICS, with the flow rate increasing, the highest posterior capsule pressure gradient areas become smaller(Fig. 3-5). For the same pressure gradient, smaller areas are more easily influenced by pressure gradients, which increases the fluctuations of the posterior capsule and the probability of PCR. Overall, in the analysis of the turbulence intensity and pressure gradient of posterior capsule, the posterior capsule instability were found to be higher in BMICS than in CMICS. The limited irrigation that occurs during BMICS has also been previously shown to cause anterior chamber instability.[9] Therefore, the bimanual irrigation and aspiration procedure required to have a lower flow resistance for the irrigation system than for the aspiration system can be achieved using cannulas with larger lumen diameters and shorter lengths.

In the present study, the anterior chamber(AC) pressure decreased linearly as the flow rate increased. Typically, below a critical flow rate, when the AC pressure becomes less than the ambient atmospheric pressure, it results in collapse of the AC. Our measured critical values of the AC pressure less than the ambient atmospheric pressure are 23.148cc/min in BMICS and 29.419 cc/min in CMICS. This simulations are similar results of existing report.[21]

This study has some limitations. While we modeled the posterior capsule as a rigid structure, it is actually a thin membrane whose various movements are influenced by fluid flow. Therefore, the present study does not account for the various sequential movements of the posterior capsule. Other factors, including surgical setting, location of the cannula tips, and surgical method used, can also influence the movement of the posterior capsule. This simulations do not present shape of remnant cataract lens and ultrasonic energy. This simulations cannot present real fluid flow of chamber and movement of posterior capsule perfectly but also can be a clue of prevalent convention which is inferred by previous studies.

Despite the limitations of the present study, our findings show that computational fluid dynamics can provide a better understanding of the fluid flow within the anterior chamber and lens cavity during phacoemulsification procedures. This is critical given that a similarly comprehensive analysis of the fluid flow cannot be obtained solely through experimental methods. Here we have shown that BMICS produces better followability of nuclear fragments. However, BMICS also increases the fluctuation of the posterior capsule and increases the risk of anterior chamber collapse. It can be a scientific clue of prevalent convention of superior in terms of followability which is inferred by previous studies. The numerical values obtained by fluid flow analysis also can be applied in the clinical field to help prevent PCR and chamber collapse.

Abbreviations

BMICS : bimanual microincision cataract surgery; CMICS : Coaxial microincision cataract surgery; PCR : Posterior capsule rupture; AC : Anterior chamber;

Declarations

Acknowledgements

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Availability of data and materials

The datasets used and/or analysed during the current study are available

from the corresponding author on reasonable request.

Authors’ contributions

SHK was involved in data collection, analysis as well as drafting the manuscript. JYK made substantial contributions to conception of the manuscript and were involved in data interpretation and revising the manuscript critically for important intellectual

content. All authors read and approved the final manuscript.

Ethics approval and consent to participate

All included trials had protocols approved by relevant country- and trialspecific

institutional review boards/independent ethics committees.

Consent for publication

Not applicable for this section.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1. The sizes of the various cannulas.

Phacoemulsification cannula type		Diameter (mm)		Total lengh (mm)
		Inner	Outer	
Bimanual,	aspiration	0.50	0.81	16
	irrigation	0.50	0.81	16
Coaxial,	aspiration	0.57	0.82	16
	irrigation	1.19	1.24	16

Table 2. The difference between outside and inside pressure of cannulas.

Phacoemulsification type	Flow rate(ml/cc)	Pressure difference (Pascal)
Bimanual,	18	0.517
	23	1.509
	28	2.219
Coaxial,	18	0.301
	23	1.266
	28	1.382

Table 3. The turbulence kinetic energy of posterior capsule surface.

Phacoemulsification type	Flow rate(ml/cc)	Turbulence kinetic energy (m^2/s^2)		Turbulence kinetic energy difference(m^2/s^2)
		Maximum	Minimum	
Bimanual,	18	0.3	0.000081	0.299919
	23	0.3	0.000081	0.199919
	28	0.15	0.000081	0.149919
Coaxial,	18	0.2	0.000004	0.199996
	23	0.15	0.000004	0.149996
	28	0.1	0.000004	0.099996

Figures

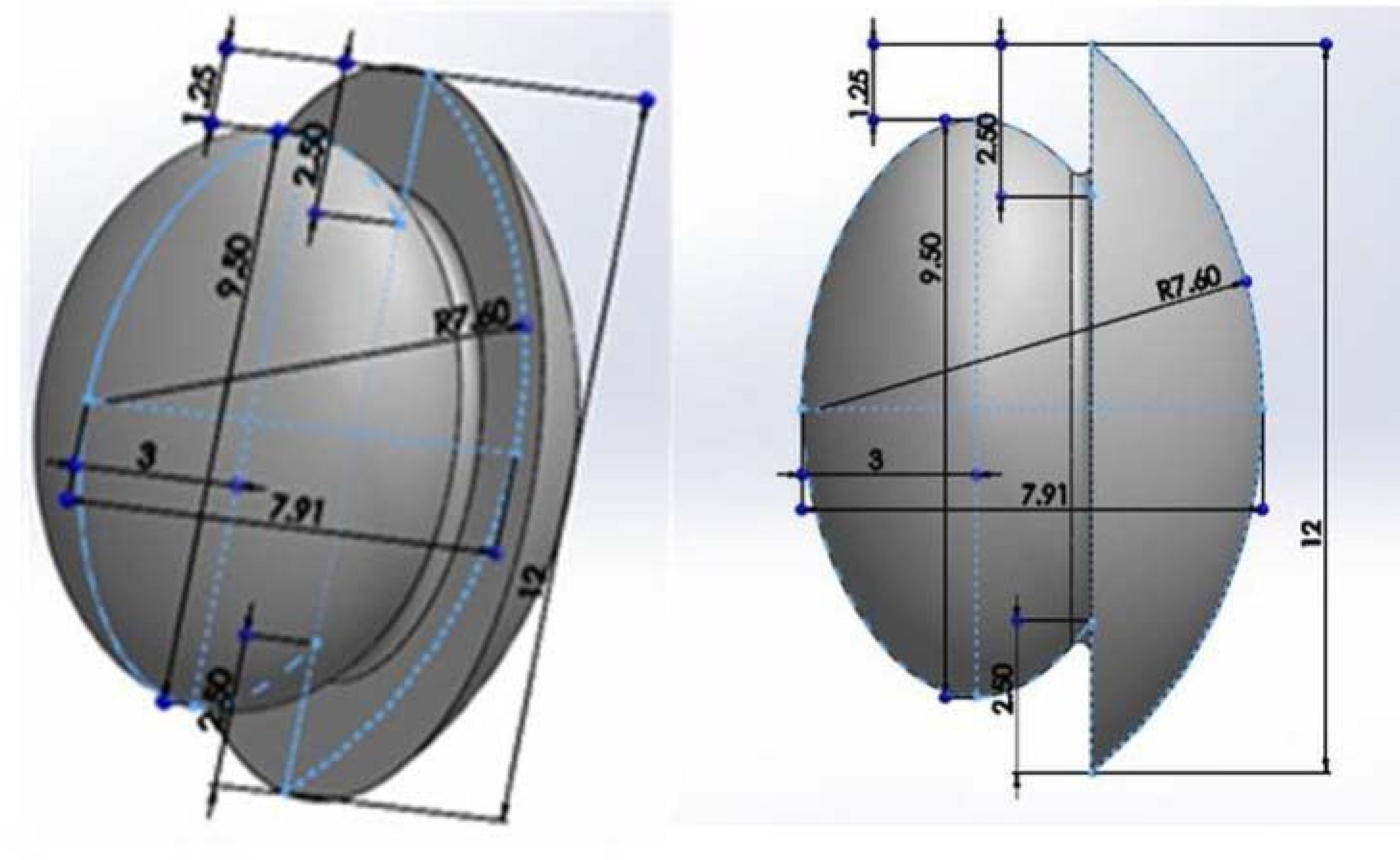

Figure 1

The schematics of the computational eye model and 3-D grid.

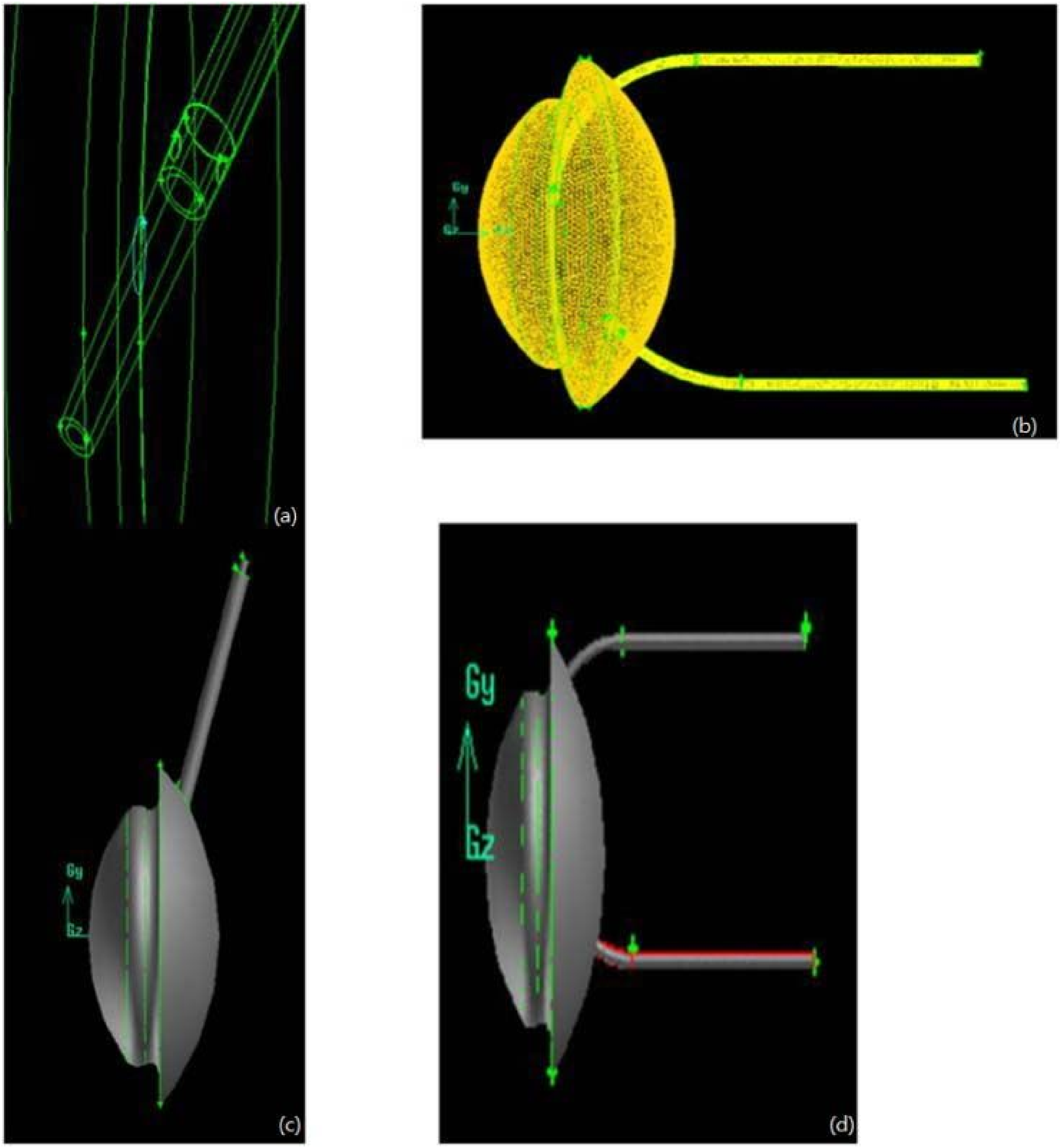

Figure 2

The grid generation and configuration. (a) Process of grid generation (b) Surface mesh of inlet and outlet for coaxial type (c) Configuration of coaxial type (d) Configuration of bimanual type

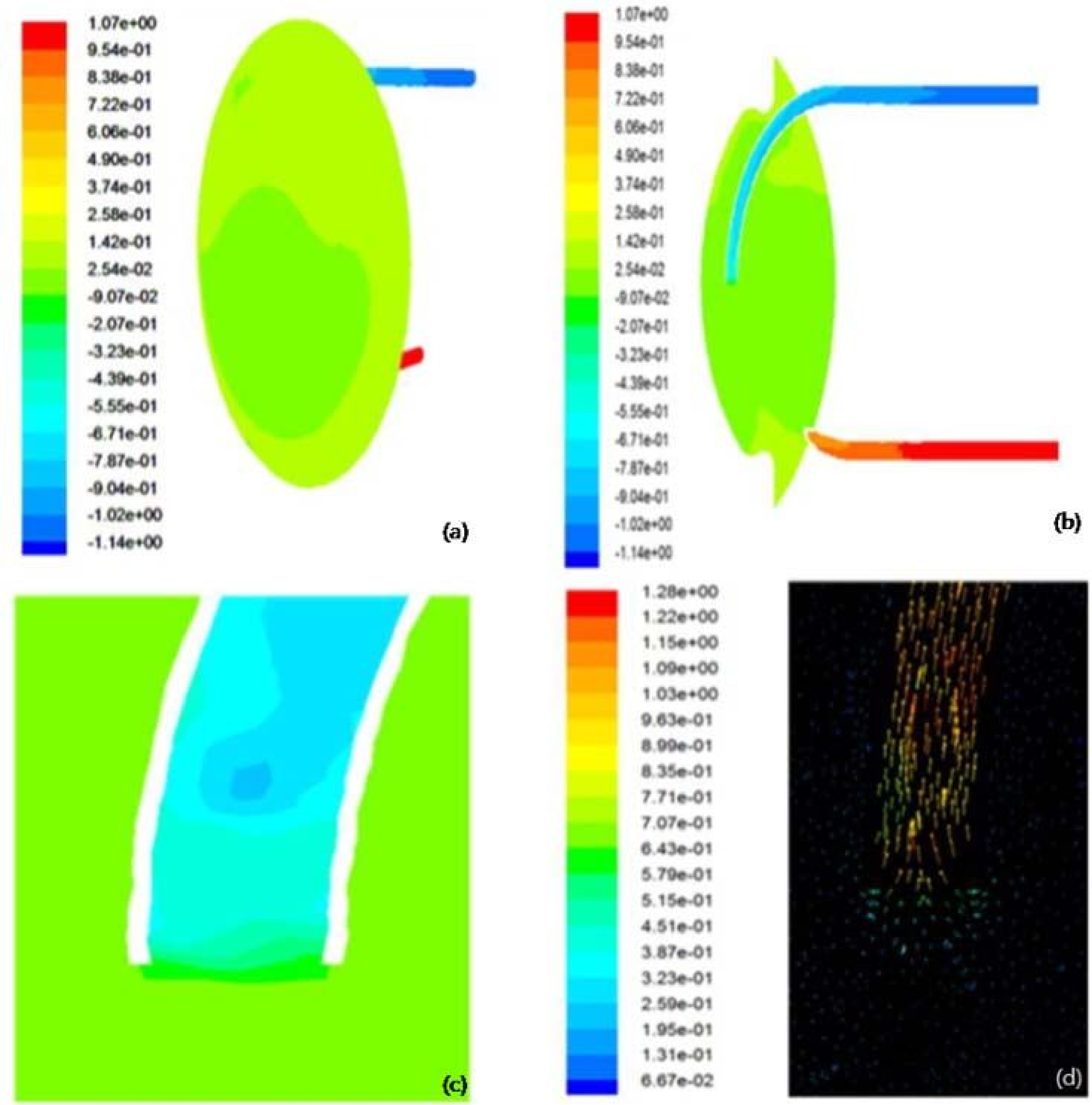

Figure 3

The computational results of bimanual type for a flow rate of 18 ml/min. (a) Pressure contour (b) Pressure of central surface (c) Pressure contour around entrance of outlet pipe (d) Velocity vector around entrance of outlet pipe

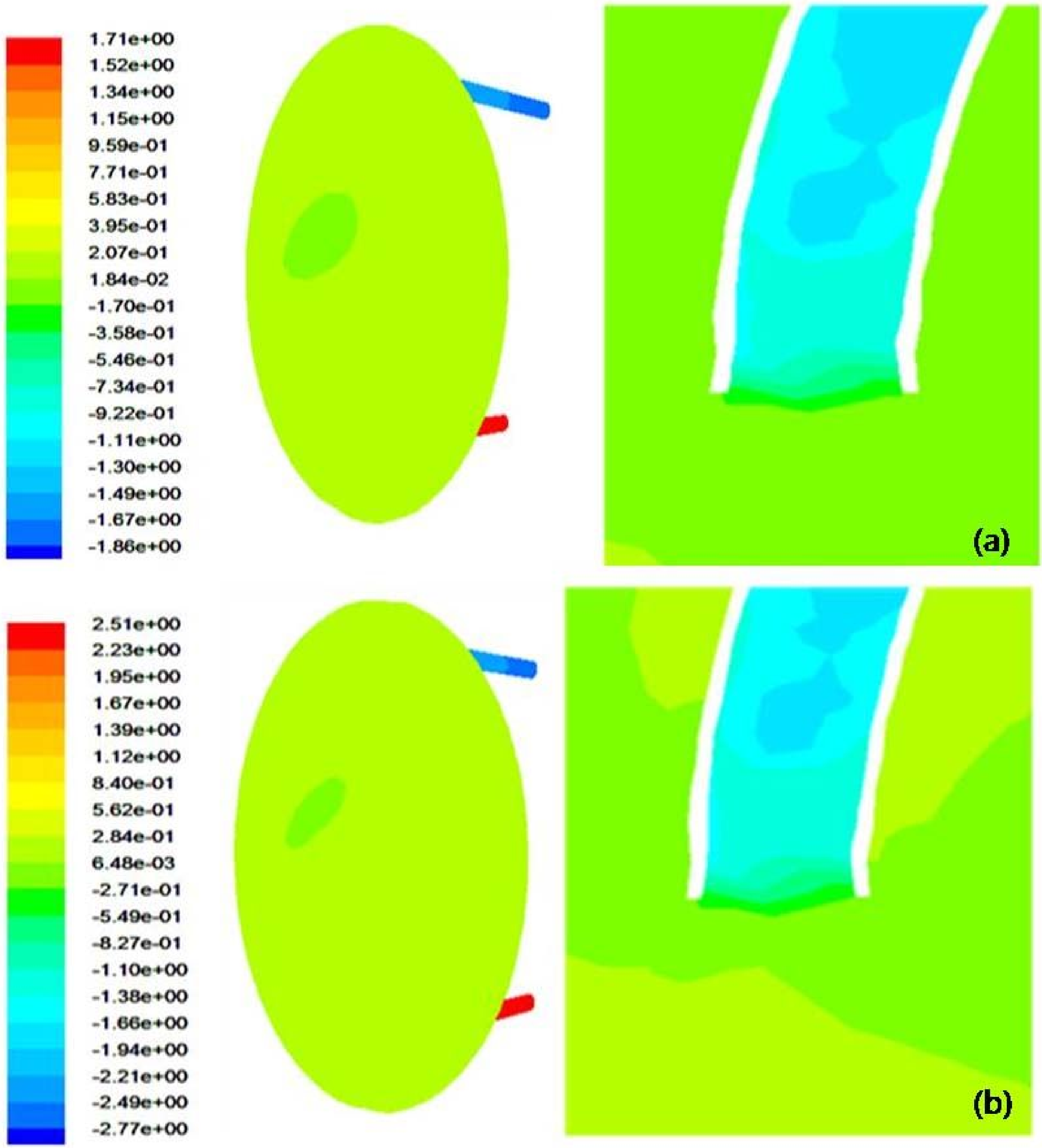

Figure 4

The computational results of bimanual type for a flow rate of 23 and 28 ml/min. (a) 3-D pressure contour, pressure contour around entrance of outlet pipe for a flow rate of 23 ml/min (b) 3-D pressure contour, pressure contour around entrance of outlet pipe for a flow rate of 28 ml/min

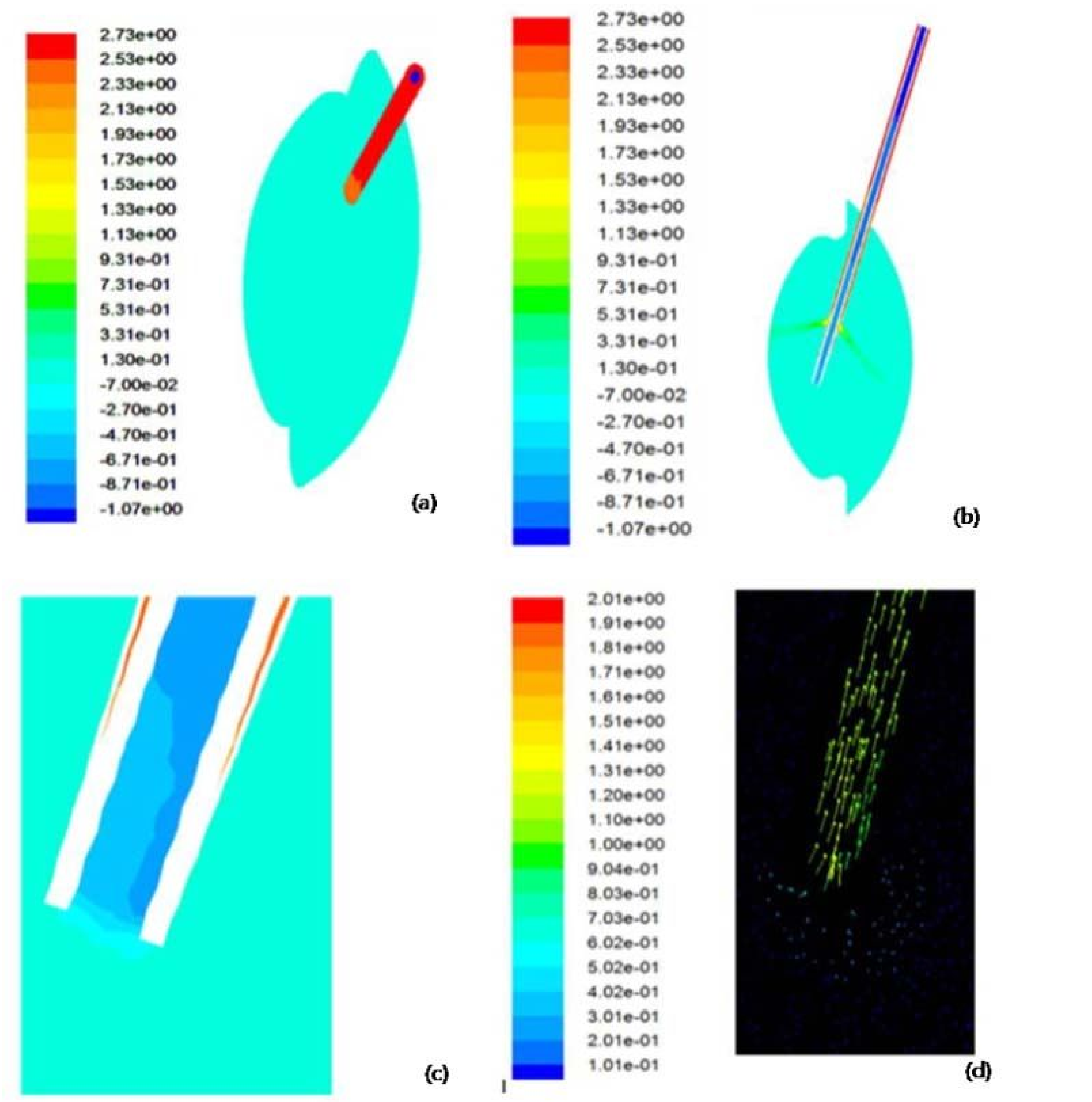

Figure 5

The computational results of coaxial type for a flow rate of 18 ml/min (a) Pressure contour (b) Pressure of central surface (c) Pressure contour around entrance of outlet pipe (d) Velocity vector around entrance of outlet pipe

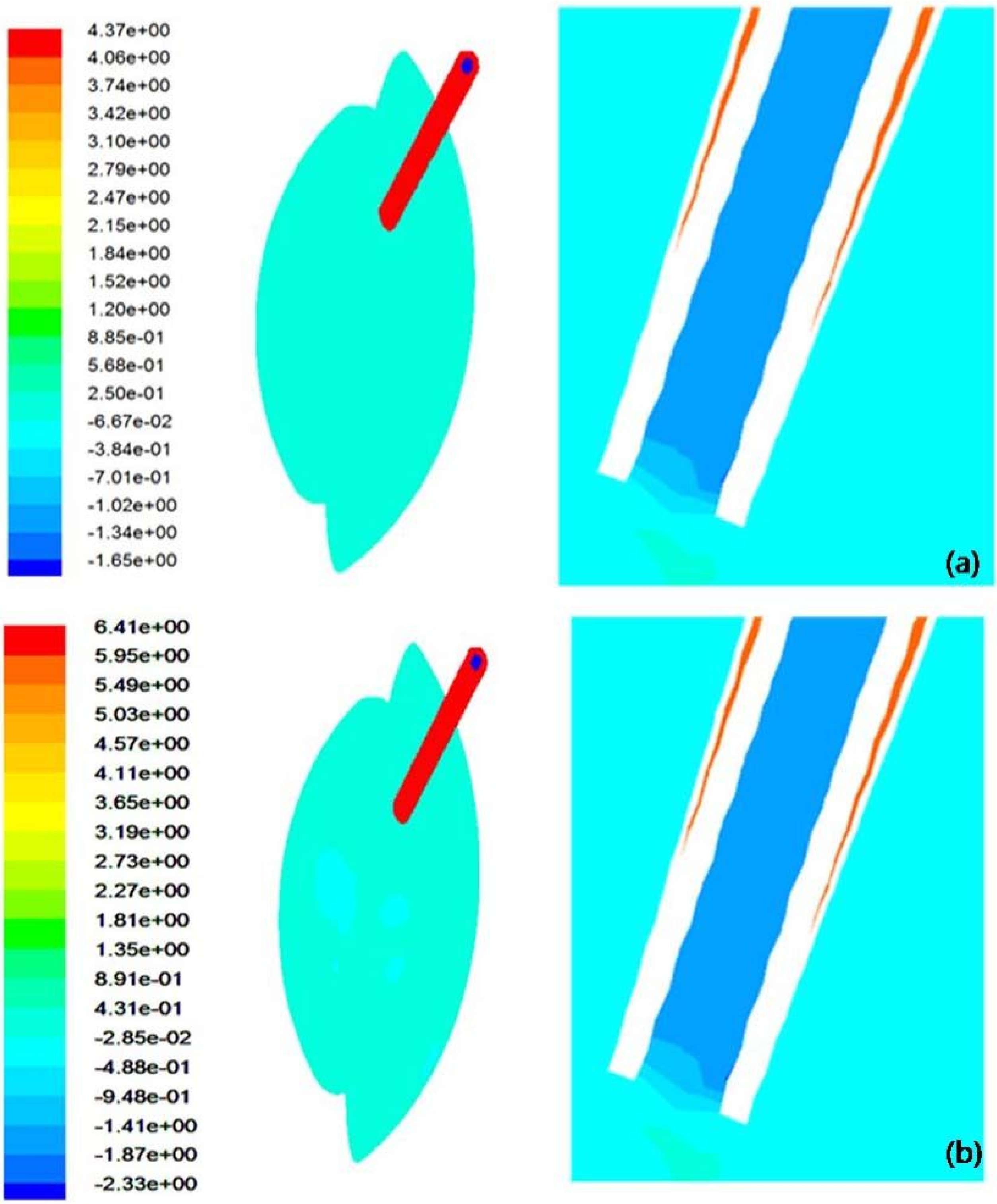

Figure 6

The computational results of coaxial type for a flow rate of 23 ml/min and 28 ml/min. (a) 3-D pressure contour, pressure contour around entrance of outlet pipe for a flow rate of 23 ml/min (b) 3-D pressure contour, pressure contour around entrance of outlet pipe for a flow rate of 28 ml/min

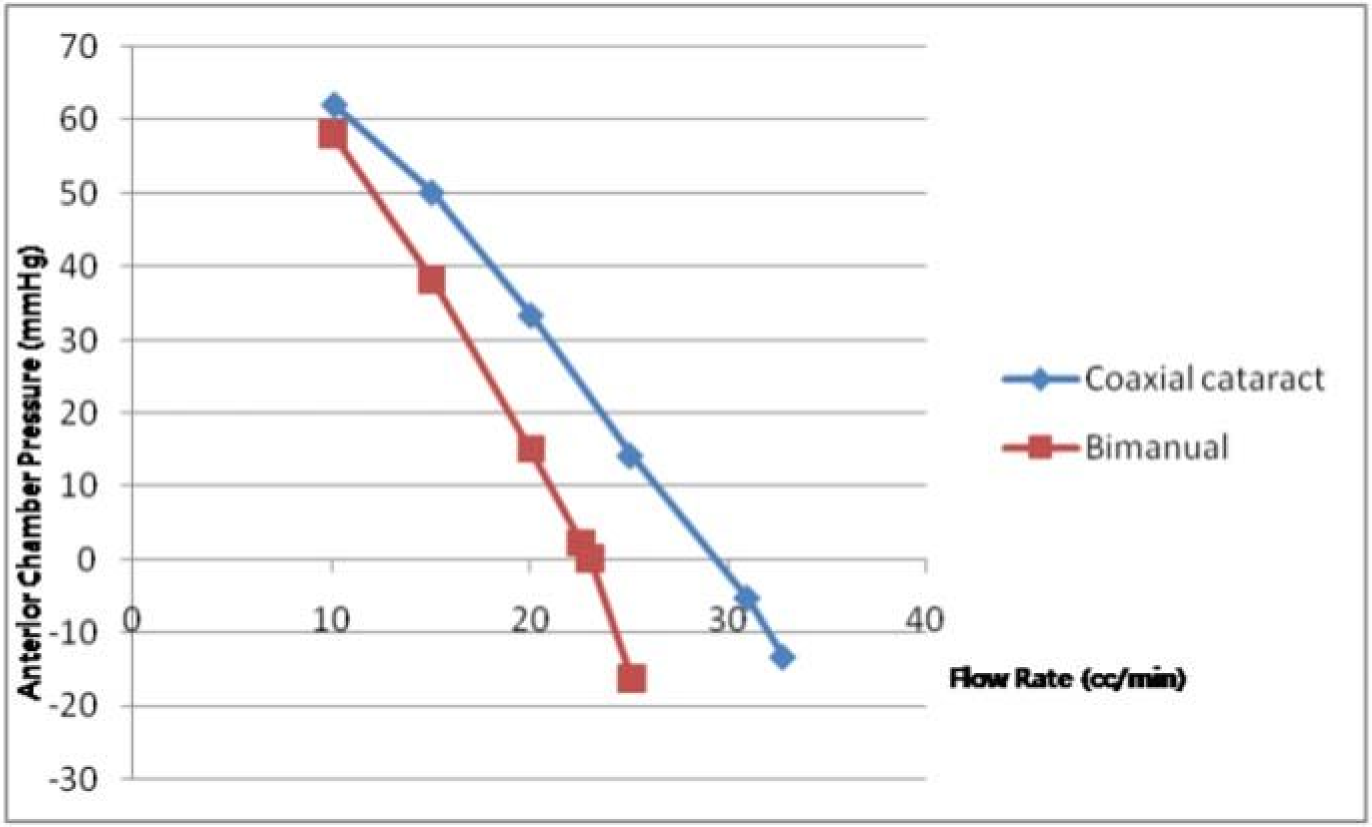

Figure 7

The predicted anterior chamber pressure change as aspiration flow rate increase for bimanual and coaxial phacoemulsification.