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Influence of compliance on flow rate waveforms in hydraulic circuits for *in vitro* modeling the human circulatory system

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Abstract. Generating an artificial blood flow in a circle system is an important step in hemodynamic research; thus, the influence of circle system components on the pulsatile flow wave forms should be investigated. In this study, a circle system was built, in which two solenoid valves were controlled by a timer to transform a constant flow into a pulsatile one, and two customized compliances with five different aeration volumes were set up upstream and downstream of the test chamber, achieving twenty-five different wave forms. Then, the influence of the compliance settings on the flow rate wave form was investigated. From the experimental data, it can be concluded that the absolute value of the maximum value and the minimum value of the wave forms increases along the aeration of the downstream compliance but decreases along the aeration of the upstream compliance. For the second maximum value and the offset between the maximum value and the minimum value, remarkable differences were obtained between runs with aeration of zero compliance and nonzero compliance. Finally, an emulational flow was achieved with the up- and downstream aeration volume equaling 360mL and 180mL, respectively, which fit the realistic wave form well.

Keywords: Pulsatile flow, compliance, particle image velocimetry, circle system, abdominal aortic aneurysms

1. Introduction

Abdominal Aortic Aneurysms (AAA) pose a serious health risk due to their potential for thrombus formation, dissection, and, more importantly, rupture [1,2]. *In vitro* studies on AAA have been performed since the end of the last century [3]. For most of the authors, research was carried out under a pulsatile flow condition [4–6]. Accordingly, the periodic pulsatile flow is one of the most important features in hemodynamic research.

To simulate the pulsatile blood flow, a number of circle systems have been created, in which compliance, pulsatile pump, and after-load are all combined to generate the pulsatile blood flow [7, 8]. Normally, the pulsatile pump generates the original flow pulsation, while the after-load works to alter the mean quantity of the flow rate. As an important component, the compliance stabilizes and alters the flow rate wave form by simulating a vascular wall's elasticity.

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However, for recent studies, the settings of circle system components differ from one another. For example, the circle system set by Salsac and Zhang did not include either the compliance or the after-load [1,4]. Chong, on the other hand, set up the compliance up- and downstream of the test chamber and did not set up the after-load [5]. Additionally, Deplano only set up a compliance upstream of the test chamber [6], whereas Gaillard [9] adopted both the compliance and the after-load. The flow rate wave forms that are generated by all of the varying systems are different from the realistic flow wave rate form. For example, the maximum value and the minimum value are smaller for the wave forms generated by Chong et al., but that produced by Salsac et al. is larger. Also, wave forms generated by Chong et al. and Zhang et al. do not present a back flow time interval, which again differs from the actual form. Moreover, for most of the wave forms generated by different researchers, the time offset between the maximum value and the minimum value is larger.

All of the above should be improved in order to achieve a realistic wave form of the human body. However, according to a careful reading of existing literatures, techniques for improving wave forms by adjusting the circle system settings have scarcely been reported. The author previously reported that different compliance settings can achieve different pressure wave forms [3]. As one step towards achieving a uniform understanding of the blood flow pattern in the human body, this study investigates the influence of compliance settings on the structure of the flow rate wave form by setting up different locations and aeration volume and then achieving an emulational flow circle.

2. Methods

2.1. Compliance

The compliance is a chamber filled with air and liquid that simulates a vascular wall's elasticity. The ratio of air volume to liquid volume in the compliance determines how much energy can be reserved at systole. Various simulations of vascular elasticity can be achieved by adjusting the ratio.

Conventional compliances cannot be matched to the circle system because of their excessive size and working pressure; therefore, a customized compliance had been developed, as shown in Fig.1. The compliance's main body is a plexiglass cylinder with a bottom diameter of 60mm and a height of 200 mm. An English-style valve core is installed through the top cover of the cylinder. Air can be pumped into the compliance by an inflator and can be discharged manually. Two horizontal tubes with a bottom diameter of 25 mm and a length of 50 mm are settled at the compliance's sides to connect it to the circle system.

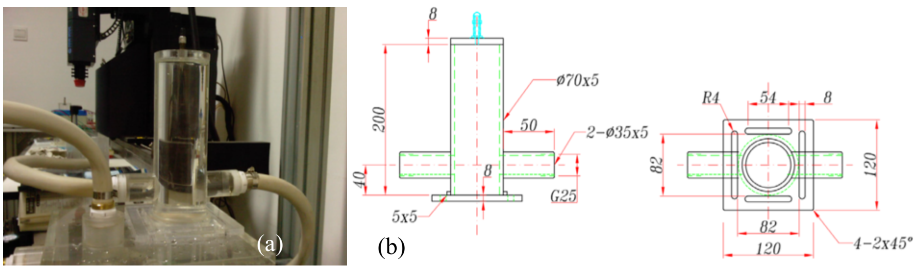

Fig. 1. Compliance model: (a) the photograph (b) the structure.

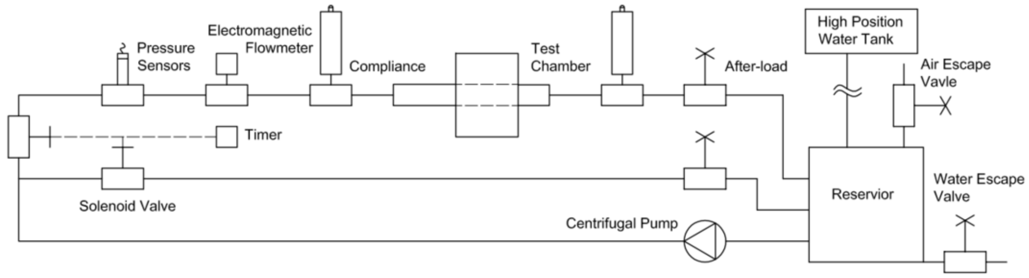

Fig. 2. Schematic of the circle system.

2.2. Flow circuit and measurement of the flow rate

2.2.1. Flow circuit setup

The circle system is shown in Fig. 2. A centrifugal pump (AC-2CP-MD Pumps, MARCH PUMPS, USA) is used to provide a steady flow. Liquid flowing from the pump is separated into two branches. One branch leads to the test chamber, and the other branch (corresponding to the redundant liquid) flows directly to the reservoir with a side length of 300 mm. Two solenoid valves (SV10075STE 3/4" True Union Solenoid Valve, HAYWARD, USA) are installed at the beginning of each branch and are controlled by a timer (SX160 Electronic Timers, EAGLE SIGNAL, USA). One solenoid valve opens when the other is closed, and vice versa. With an alternating sequence of closing and opening the two solenoid valves, a steady flow can be converted into a pulsatile one. The open and close durations are set as 0.20 s and 1.00 s, respectively, to achieve a pulsatile period equaling 1.2 s. Finally, liquid converges in the reservoir, and after rectification, it is removed by the pump, and a new cycle begins.

Two compliances were installed, both upstream and downstream of the test chamber, and five different aeration volumes of the compliance (ranging from 0 to 360 mL in 90 mm increments) were adopted as well, which results in different flow rate wave forms. Furthermore, an after-load was introduced to simulate the peripheral resistance of the micro-vessels and capillaries. Moreover, a high position water tank was used to achieve a steady backpressure, and finally, an electromagnetic flowmeter (AMF300-15-S-NNN-N and AMC2100-AC-CP-NN, Alia Group Inc., USA) was used to measure the mean flow rate through the test chamber.

2.2.2. Flow rate measurement

The particle image velocimetry (PIV) is widely used to measure the fluctuation of the flow field [10]. In this paper, a Q-switched, double cavity pulsed Solo PIV Nd: YAG Laser (NewWave, USA) was used as the illumination source. This illumination source had a sampling rate of 15Hz and a maximum energy per pulse of 150 mJ. Two thin, green laser sheets were generated to illuminate the plexiglass test chamber with a satisfactory light transmittance. In order to eliminate any diffused reflection on the air-plexiglass contact, the test chamber was surrounded by a water jacket, as shown in Fig. 3(a). The flow was seeded with 8μm hollow spheres (TSI, USA). A high speed charge-coupled device camera (PCO.1200, COOKE, GER) and a 60mm micro-lens (Nikon, JAP) were positioned normally to the laser sheet. The synchronizer (610034, TSI, USA) was used to coordinate the camera and the laser.

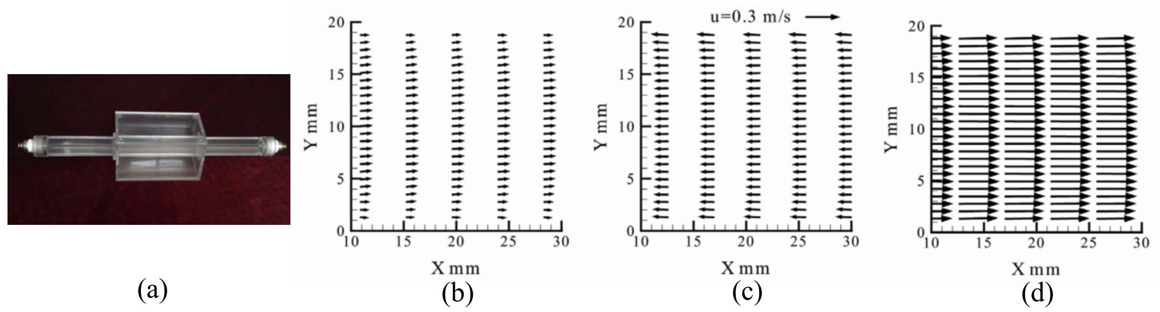

Fig. 3. (a)The test chamber and flow field for three typical instants: (b) front-systole, (c) peak-systole and (d) end-systole.

As the sampling rate is 15Hz and the pulsatile period is 1.2 s, 18 instants are determined in one period. Each run contains approximately 40 periods. Each run's images were analyzed with a cross-correlation algorithm to yield the flow field in the central section of the test chamber. Flow fields in three typical instants (the front-systole, peak-systole, and end-systole) are shown in Fig. 3(b-d), with all flow fields, the flow rate for each instant can be calculated. The root mean square error is 0.004. Finally, the wave form in each run is represented by the phase-averaged flow rate of the aforementioned 18 instants.

3. Results and discussion

3.1. Parameters of the structure

As mentioned in Sec. 2.2.1, five different aeration volumes were adopted for each compliance, and there are two compliances in the circle system. Therefore, a total of 25 runs, specified by the up- and downstream aeration volumes (V_{up} and V_{down}), were carried out.

Several of the structure's parameters should be defined. Parameters are identified by comparing the wave forms in all runs, as shown in Fig. 4, including the values of the extreme points on the wave form, the maximum value (Q_{max}), the minimum value (Q_{min}), the second maximum value (Q_{max1}), and the offset between the Q_{max} and the Q_{min} ($T_{max\text{-}min}$).

3.2. Values of the extreme points

The Q_{max} values in all runs are shown in Fig. 5(a). It can be noted that the Q_{max} increases along the V_{down} but decreases along the V_{up}. If a wave form with a larger Q_{max} is desired, one way to achieve it is to increase the V_{down}. For instance, a remarkable increase of the Q_{max} by 2 L/min can be achieved by increasing the V_{down} from 0 mL to 90 mL. However, the more V_{down} increases, the more the resulting

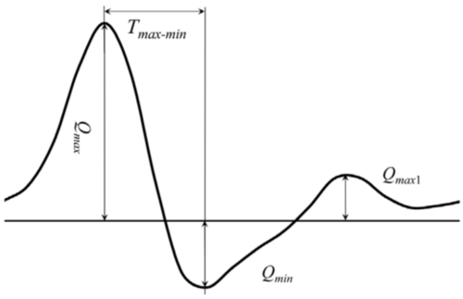

Fig. 4. Parameters of the wave form structure.

Q_{max} increase will slow down. Only an increase of 1L/min can be achieved when the V_{down} increases from 90 mL to 360 mL. As previously mentioned, Q_{max} can also be increased by decreasing the V_{up}. Decreasing V_{up} by 360 mL can increase the Q_{max} by a total of approximately 2 L/min. However, if a wave form with a smaller Q_{max} is desired, an inverse process can be applied.

The Q_{min} values in all runs are shown in Fig. 5(b). The situation for the Q_{min} is a bit different. The Q_{min} decreases along the V_{down}. However, it should be noted that the Q_{min} is not monotonically increasing with the V_{up}, as it turns out to be the minimum value with the V_{up} is equal to 90 mL. That means that if a wave form with a smaller Q_{min} is desired, increasing the V_{down} is a good choice. However, if we want to achieve it by adjusting the V_{up} instead, V_{up} should be set at only 90 mL, neither lower nor higher. In addition, with the V_{down} equal to zero, the Q_{min} cannot be changed. These results are interesting. If we got an original wave form with a Q_{min} that is different from the realistic one, the downstream compliance must be settled, otherwise the Q_{min} cannot be changed. Moreover, the Q_{min} decreased more when V_{down} was increased from 0mL to 180 mL; the decrease stopped only after the V_{down} had increased to more than 180 mL. The Q_{min} can only be decreased to no smaller than 6 times the original value by the increase of the V_{down}. Thus, there is a limitation imposed on the Q_{min} minimum by setting up the compliance; V_{up} should be set to 90 mL and V_{down} to greater than 180 mL in order to achieve it.

The change of the Q_{max1} is shown in Fig. 5(c). The run with the V_{up} equaling zero is obviously different from the others with nonzero values for the V_{up}. The inner air in the downstream compliance can draw liquid from the test chamber at peak-systole, resulting in an increase in the Q_{max1} by 2 L/min along the V_{down} from 0 mL to 360 mL. However, when the V_{up} is not zero, the upstream compliance steadies the Q_{max1} by absorbing and discharging the energy at diastole. As a result, the Q_{max1} equalizes to 1.6 L/min with a nonzero V_{down}. Accordingly, the Q_{max1} in a realistic wave form is always small, thus the V_{up} should be larger than zero to keep a low Q_{max1}.

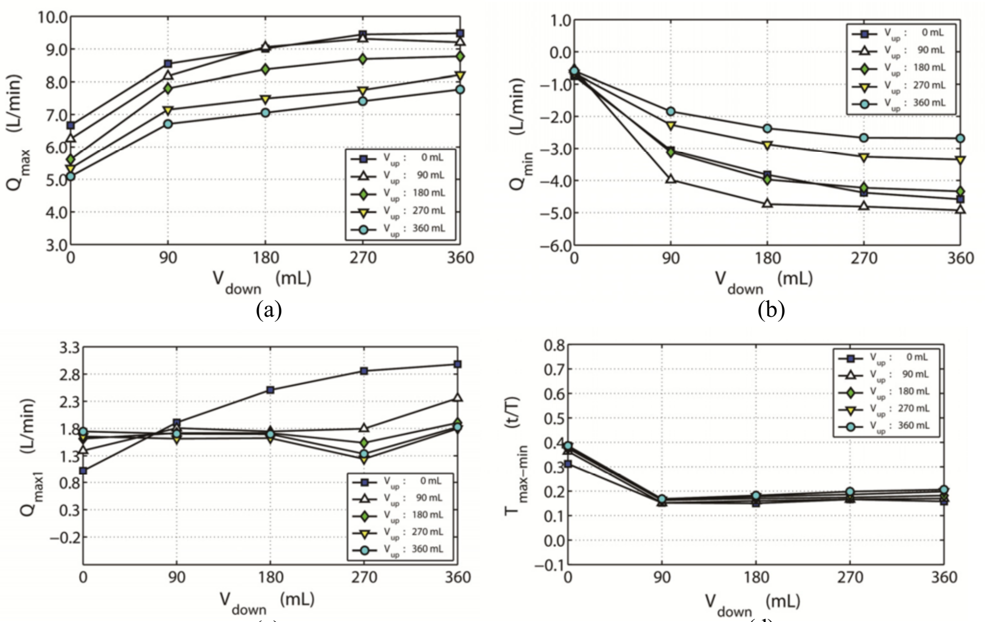

Fig. 5. Influence of the compliance on the flow rate wave form: (a) The maximum value (Q_{max}), (b) The minimum value (Q_{min}), (c) The second maximum value (Q_{max1}), and (d) The offset between Q_{max} and Q_{min} ($T_{max\text{-}min}$).

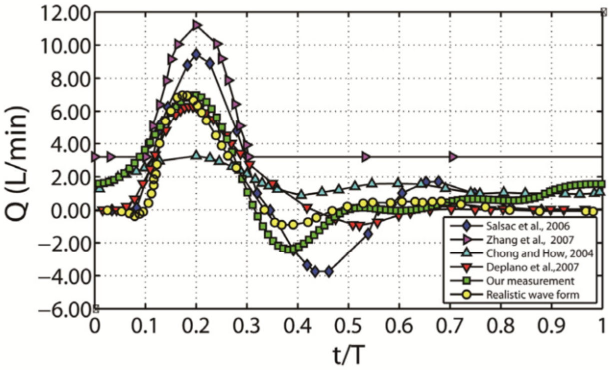

Fig. 6. Comparison of realistic wave form and the *in vitro* experiments.

3.3. Offset between extreme points

The $T_{max\text{-}min}$ is shown in Fig. 5(d), and displays an interesting result. When the V_{down} equals zero, it turns out to be an original wave form in the test chamber. Once the V_{down} is larger than zero, the downstream compliance works, and the energy discharged by the inner air in the downstream compliance then results in a powerful reverse flow. This yields a new wave form with a short offset $T_{max\text{-}min}$. Therefore, in the graph, the $T_{max\text{-}min}$ drops from 0.37 to 0.17 as V_{down} increases from 0mL to 90 mL; then, it remains almost unchanged as V_{down} increases from 90 mL to 360 mL. Conversely, the upstream compliance has minimal influence on the $T_{max\text{-}min}$, as its primary function is to flatten the wave form and reduce the velocity of the forward flow. As a result, the $T_{max\text{-}min}$ only slightly increased along the V_{up}. For most of the wave forms generated in the past study, the $T_{max\text{-}min}$ was larger than the realistic one. In this situation, adding a downstream compliance is a reasonable measure.

3.4. The wave form generated by the circle system

Based on the above-mentioned rules about how the compliances influence the flow rate wave form, an emulational flow rate wave form is finally generated with V_{up} equal to 360 mL and V_{down} equal to 180 mL, as shown in Fig. 6. The realistic wave form is determined from magnetic resonance measurements [11]. Of notable interest, the Q_{max} and $T_{max\text{-}min}$ of the present wave form fit well with the realistic one, the relative differences of which are 0.0037 and 0.023, respectively. The Q_{min} is a bit lower, but the difference is smaller than for most of the other wave forms. Such an emulational flow rate wave form could be used in AAA *in vitro* experimental measurements by changing the test chamber with an AAA model. The drawback of this wave form is that the flow rate is larger at the initiation of the systole. In the future, it should be optimized by other means. Furthermore, the above-listed rules can be used in other artery experimental studies that are based on a pulsatile flow circle system with a compliance.

4. Conclusion

A circle system has been built in order to generate a pulsatile flow rate similar to the one found in the human body, in which a centrifugal pump is used as a steady power source and a solenoid valve is controlled by a timer to generate a pulsatile flow similar to the one produced by a heart. Two customized compliances with five different aeration volumes were set up both upstream and downstream of the test chamber, and twenty-five different flow rate wave forms were generated by different settings and acquired by a PIV system. The influence of the compliance setting on the flow rate wave form was investigated. From the experimental data, it can be concluded that compliances with different settings can change the structure of the flow rate wave form. The maximum value and the minimum value of the wave forms can be easily adjusted. In comparison, the second maximum value and the offset that is between Q_{max} and Q_{min} is hard to change. For most parameters, there is a remarkable change between runs when the aeration of the compliance equals zero and runs with a larger aeration. Moreover, there is a limitation imposed on the achieved minimum value by the downstream compliance. According to the rules detailed above, an emulational flow rate wave form has been achieved with V_{up} equal to 360 mL and V_{down} equal to 180 mL, which fits the realistic wave form well.

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