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Analysis of the strain-pressure relation imposed via physiological pulsatile flow at the aortic isthmus

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1. Introduction

The aorta is the main blood artery that delivers blood to the rest of the body. Aortic dissection or traumatic rupture, often occur on the aortic arch. The mechanisms involve a relation between the intraluminal pressure and the resultant deformation. To understand these mechanisms, the coupling of hemodynamics and surface deformation of the arterial wall, should be examined (Borghi et al. 2008). For a detailed investigation of realistic loading conditions, mock circulatory loops to test the aorta under haemodynamic conditions have been developed. Circulatory loops are very useful to test in-vitro arteries by mimicking physiological pulsatile blood pressure and flow. They offer the advantage of the simultaneous measurement of the flow parameters and deformation of the arterial wall (Franchini et al. 2021). The main goal of this study was to analyse the effect of the pressure wave on the deformation of the aortic arch. For that purpose, the surfacic Green-Lagrange (GL) strain field at the outer aortic wall during a cardiac pulse was measured using digital image correlation (DIC).

2. Methods

2.1 Specimen Preparation

A porcine cardiopulmonary system was obtained from a local butcher. Only the heart, the pulmonary arteries and the aorta were kept. The pulmonary arteries were preserved to maintain the connection with the aorta through the arterial ligament. The soft connective and adipose tissue were removed. Ligatures were made on the azygos vein and sutures were applied to the arterioles along the aorta. A cannula was inserted into the left ventricle for the inlet flow that simulates systemic circulation. A cannula was inserted at the descending thoracic aorta to allow the outlet flow. A fine and irregular random speckle pattern was applied at the aortic isthmus for DIC.

2.2 Test Set-up and instrumentation

A specific mock circulatory loop was designed to mimic and monitor aortic haemodynamical flow with reasonable accuracy by reproducing pulse rate, and pressure conditions (see Tresson et al. 2023 for a detailed description). The heart-aorta system was mounted on a rigid support to maintain its position and orientation in a physiological manner.
A miniature pressure sensor was placed close to the aortic arch through the left carotid. Ligatures were made to ensure system sealing. Pressure signal was recorded at 2 kHz. Two high-speed digital cameras were set up to measure the deformation using DIC. Video recording was performed at 250 Hz.

2.3 Data Processing and analysis

The displacement at the outer surface, in cylindrical coordinates, was extracted using VIC3D® software. The software allowed for the calculation of the 3 components of the surfacic GL strain field. The principal strains were also computed by the software.
Theoretically, any periodic function, $S(t)$, can be expressed using a Fourier series which frequencies are

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harmonics of the main frequency (a cardiac frequency of 1Hz in our case).

$$s(t) = A_0 + \sum_{n=1}^{N} A_n \cos\left(n\omega t - \phi_n\right)$$

Where ω is the pulsation (rad/s), A_n is the amplitude and ϕ_n the phase of the nth harmonic.
Previous study (Van der Vosse and Stergiopulos 2011) has shown that the first five harmonics contain over 90% of the energy of the pressure wave and are sufficient to reconstruct pressure waveforms. Then any characteristic of the system response can be determined separately for each harmonic by their amplitudes and their phases. In the following, only the four first harmonics of the principal strain and of the pressure are discussed since the 5th harmonic and higher represent less than 1% of the 1st harmonic.
For each signal, the amplitudes and phase angles were normalised to the values of the 1st harmonic: $\tilde{A}_n = \frac{A_n}{A_1}$ and $\tilde{\phi}_n = \phi_n - \phi_1$. The phase shift between the pressure and each principal strains was also defined for each harmonics as $\tilde{\varphi} = \phi_{nE_i} - \phi_{npressure}$ and the phase shift between the two principal strain as $\tilde{\psi}_n = \phi_{nE1} - \phi_{nE2}$.

3. Results and discussion

The Figure 1 shows the changes in amplitudes and phase angles of the first five harmonics of the pressure wave and of the principal strains. The maximal value of the pressure was 16 kPa and the minimal 9.3 kPa in accordance with the physiological values. The 1st principal strain (the circumferential direction) was found two times greater the 2nd principal strain (axial direction) due to the anisotropy of the aortic tissue.
The amplitude of the pressure decreased with the frequency as expected. A similar trend was observed for the principal strains. However, the decrease was less for the 2nd principal strain and the for the pressure than the 1st principal strain.
The Figure 1 shows also that phase angles varied with the frequency. For the pressure, after an increase between the 1st and the 2nd harmonic, the phase lag decreased with the frequency. While the phase lag for both strains showed a continuous decrease with frequency.
Although the principal strains showed a strong anisotropic behaviour, they were relatively in phase. In contrast, the phase shift between the principal strains and the pressure demonstrated a large decreased between the two first harmonic.

Then, the phase shift decreased continuously with the frequency (Table 1). The identification of phase lags between the intraluminal pressure and the strain can be related to the viscous behaviour of the aortic wall

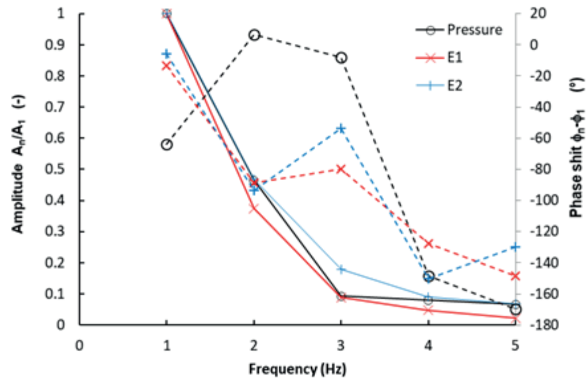

Figure 1. Principal strains and Pressure amplitude (solid line) and phase shift (dotted line) vs. frequency (i.e. harmonics).

Table 1. Comparison of phase shift between the principal strain and the pressure for each frequency.

Frequency (Hz)	$\tilde{\varphi}_{n1}$ (°)	$\tilde{\varphi}_{n2}$ (°)	$\tilde{\psi}$ (°)
1	50.3	58.0	-7.8
2	-95.0	-99.8	4.7
3	-71.5	-45.4	-26.1
4	20.8	-1.9	22.7
5	21.4	39.9	-18.5

The phase lags represented the time delay between the loading (pressure) and the deformation (strain) of the wall that is a characteristic of a viscous behavior.

4. Conclusions

An experimental study was performed to determine the effect of a physiological pulsatile flow on the surfacic strain field at the aortic arch. The relation between the pressure wave resulting from the pulsatile flow and the principal strains was investigated
For that purpose, a Fourier series analysis was performed and the characteristics (amplitude and phase) of the five first harmonics of the pressure and strain wave were discussed. The results showed variation, e.g. decrease

of the amplitude with the frequency, of the pressure and of the principal strains.

The phase shift has more complex behavior and differences between the pressure and the two principal strains were found due to viscoelastic properties of the aorta. The time delay between applied pressure and the resulting wall deformation varied with the frequency and was found greater for the 2nd and 3rd harmonics. Variations were also observed between the two principal directions due to the anisotropy of the arterial wall.

Conflict of Interest Statement

The authors certify that they have no conflict of interest.

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