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Cross-sectional compliance overestimates arterial compliance because it neglects the axial strain

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Summary

A high resolution echo-tracking system permits the calculation of cross-sectional compliance considering vessel diameter variations alone, and assumes that longitudinal movement of the vessel wall due to pulse pressure is negligible. However, using piezoelectric crystals sutured on the adventitia of the vessel wall we demonstrated that arterial length changes up to 5% (mean 2.7%) as a function of pulse pressure. Therefore, cross-sectional compliance seems to provide a limited approximation of the real phenomenon because it neglects axial vessel movement. Axial vessel movement is taken into account when the vessel compliance is calculated according to the principle of continuity of the mass:

$$C_d = \frac{Q_{in} - Q_{out}}{\Delta P / \Delta t}$$

To verify this hypothesis we measured the blood flow gradient through 10 cm long segments of 10 pig carotid arteries ($Q_{in} - Q_{out}$) and divided it for the derivative of blood pressure over a given time ($\Delta P/\Delta t$). For the same vessels, we calculated the cross-sectional compliance (CC) using the echo-tracking system (NIUS 02). We found a CC of $(5.91 \pm 0.4)\times10^{-7}$ µm²/mm Hg and a segmental carotid compliance or *dynamic compliance* (C_d) of $(6.21 \pm 0.2)\times10^{-8}$ µm³/mm Hg. The impact of axial strain in calculations of compliance results in a dynamic compliance, which is one order of magnitude smaller than traditionally calculated arterial compliance.

Key words: arterial compliance; arterial wall; vascular ultrasound

Introduction

Compliance describes the amount of change in vessel wall dimension after application of stress. It is expressed as the ratio between vessel volume variation (ΔV) during the cardiac cycle and pulse pressure (ΔP) at a given time and in a considered vessel segment: $C = \Delta V / \Delta P$ (1). The high resolution echo-tracking system allows precise measurement of local cross-sectional compliance considering only vessel diameter variations, assuming that longitudinal movement of vessel wall is negligible [1, 2]. Hence, in clinical practice, vascular compliance is expressed as the ratio between vessel cross-sectional area and pulse pressure (cross-sectional compliance). We have demonstrated that pig carotid artery has a systolic axial shortening of up to 5% (mean 2.7%) of the considered segmental vessel length as a function of pulse pressure [3]. Therefore, calculation of arterial compliance deserves reappraisal because we can no longer neglect the longitudinal strain, as cross-sectional compliance does. According to the principle of continuity of mass we propose a method to calculate arterial compliance that takes into account axial arterial movement.

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Methods

In 10 pigs (45–55 kg), under general anaesthesia (Halothane 1.5%), we exposed the left carotid artery and placed 2 high fidelity flowmeter probes (Medi-Stim perivascular flowmeter probes, size 4 mm, flow accuracy of 1%, resolution of 1 ml/min, flow sample rates 333 Hz) on it at a distance of 10 cm (Figure 1). We inserted a high fidelity pressure probe (Millar MPC 500, pressure range –50 ÷ 300 mm Hg, sensitivity of 5 μV/V/mm Hg) in the left cervical artery up to the origin of the carotid artery. All probes were connected to a data acquisition program which displays and compares the information gathered (Medi-Stim system®). The flowmeter probes were switched into inflow and outflow position three times per animal in order to avoid hypothetical interference due to probe sensitivity. Data collections were carried out for a period of 5 consecutive seconds at least 4 times per minute for no less than 1 hour per animal. To calculate CC we used a high resolution echo-tracking system (NIUS 02) as is shown in Figure 2.

According to the principle of continuity of the mass, arterial compliance can be expressed as:

$$C_d = \frac{Q_{in} - Q_{out}}{\Delta P / \Delta t} \quad (2)$$

where Q_{in} is the instantaneous blood inflow in a given arterial conduit; Q_{out} is the blood outflow in the same conduit at the same time; the difference between Q_{in} and Q_{out} represents the energy converted in the vessel wall deformation during blood displacement and is identified as phase shift (φ). C_d is what we have called the vessel wall dynamic compliance; $\Delta P/\Delta t$ is the derivative of pressure in considered interval of time. To calculate carotid maximal dynamic compliance, we considered the maximal phase shift between inflow and outflow and calculated the correspondent $\Delta P/\Delta t$ (sampling rate 0.0022 sec).

Data are expressed as mean and s.d.

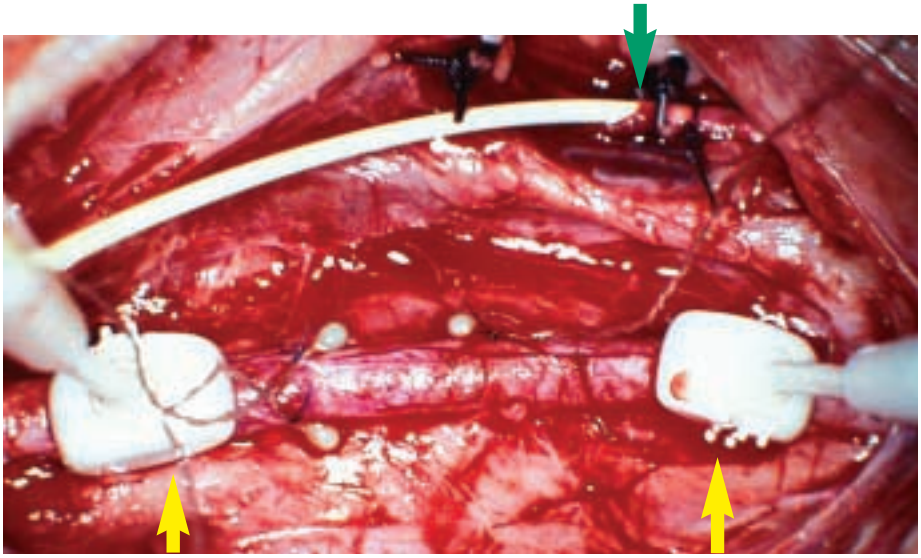

Figure 1

The left carotid artery of 48 kg pig has been isolated. Proximal part of the artery is on your right. 2 high fidelity 4 mm flowmeter probes (yellow arrows) are placed at a distance of 10 cm from each other, across the artery. A high fidelity pressure probe (green arrow) has been inserted in left cervical artery up to the origin of carotid artery .

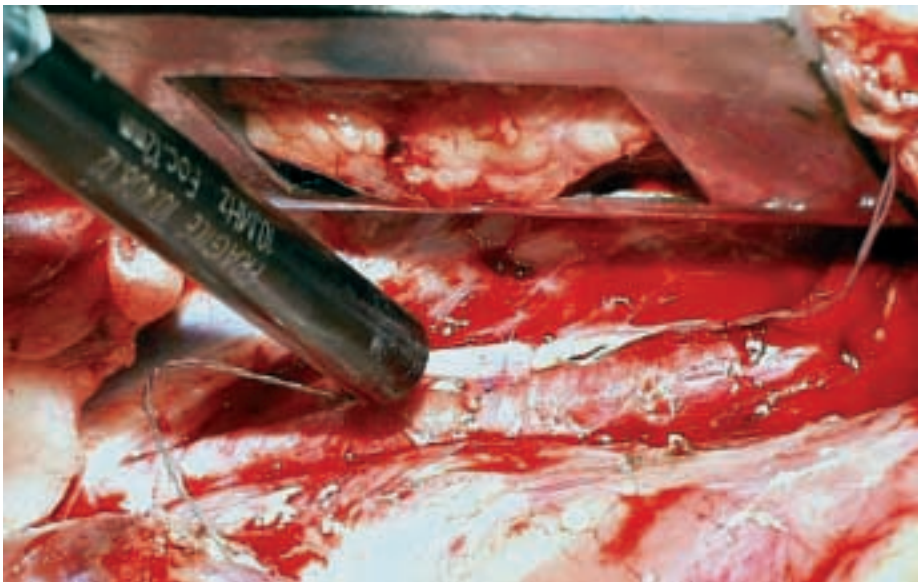

Figure 2

The left carotid artery has been exposed and the cross-sectional compliance is calculated using the echo-tracking system (NIUS).

Results

The mean arterial length (L) of the considered arterial conduit is 10 ± 0.4 cm. Instantaneous mean inlet blood flow (Q_{in}) is 284 ± 6 ml/min. Instantaneous mean outlet blood flow (Q_{out}) is 286 ± 6 ml/min. Phase shift (φ) between inlet and outlet flow (Q_{in} vs Q_{out}) is recorded in Figure 2. Mean difference between instantaneous inlet and outlet flow (ΔQ) is (0.84 ± 3) × 10^{-6} μm³/sec. Mean pulse pressure is 38 ± 13 mm Hg. Mean ΔP/Δt is 13.52 ± 8 mm Hg/sec. Mean instantaneous C_d based on maximal φ is (6.21 ± 0.2) × 10^{-8} μm³/mm Hg or 4.66 × 10^{-9} m³/kPa (range from 3.89 × 10^{-9} to 4.92 × 10^{-9}) (1 kPa = 7.5 mm Hg). Mean CC is (5.91 ± 0.4) × 10^{-7} μm²/mm Hg.

Discussion

The classical definition by Spencer and Denison [4] of compliance (C) is the change in the arterial blood volume (ΔV) due to a given change in arterial blood pressure (ΔP), ie, C = ΔV/ΔP *(1)*. If we consider the vessel as a perfect cylinder the equation *(1)* becomes:

C = (L × CC) + A × ΔL/ΔP *(3)* where L is vessel length, CC the cross-sectional compliance, A the cross-sectional area, and ΔL the vessel shortening during the cardiac cycle.

This definition is still accepted and therefore compliance is expressed in μm³/mm Hg or m³/kPa. In clinical practice cross-sectional compliance is calculated assuming that vessel volume changes during the cardiac cycle are mostly due to changes in vessel diameter with arterial elongation being considered to be negligible in vivo (ΔL/ΔP = 0). Thus, assuming L = 1, the equation *(3)* becomes: C = CC. Cross-sectional compliance[5] is defined as the ratio between variations in arterial cross-sectional area (ΔA) and blood pressure (ΔP), ie, CC = ΔA/ΔP (*4*). CC is expressed in μm²/mm Hg or m²/kPa. A high resolution pulse echo-tracking device (NIUS 02) has been used to acquire data concerning inner and outer vessel diameter and blood pressure. Then the cross sectional compliance is calculated based on the two-element Windkessel model [6]. Thus, in clinical practice, local arterial compliance can be estimated through the variation in arterial cross-sectional area and blood pressure [1, 2] and it is expressed in μm²/mm Hg.

Table 1

Data collected from 2 high fidelity flowmeter probes placed on carotid artery of 10 pigs, at a distance of 10 cm from each other. Q_{in} is the blood flow in the proximal part of the considered vessel. Q_{out} is the blood flow in the distal part of the considered vessel. Dynamic Compliance is expressed in μm³/mm Hg. φ is the phase shift between inlet and outlet flow.

	Mean and s.d.
Inlet blood flow (Q_{in})	284 ± 6 ml/min
Outlet blood flow (Q_{out})	286 ± 6 ml/min
Maximal instantaneous ΔQ ($Q_{in} - Q_{out}$)	0.84 ± 3 × 10^{-6} μm³/sec
Pulse pressure	38 ± 13 mm Hg
ΔP /Δt	13.52 mm Hg/sec
Dynamic compliance C_d (maximal φ)	6.21 ± 0.2 × 10^{-8} μm³/mm Hg
Cross-sectional compliance CC	5.91 ± 0.4 × 10^{-7} μm²/mm Hg

In our experience, pig's carotid artery shows an important axial movement detected with piezoelectric crystals sutured on it [3]. What we have called the "systolic arterial shortening phenomenon" is characterised by a decrease in vessel length of up to 5% (mean 2.7%) when vessel diameter increases, according to pressure increase [3]. Neglecting this phenomenon in the computation of compliance could lead to an overestimation of the volumetric elastic properties of the vessel. The method we propose to calculate the compliance is based on the principle of continuity of the mass and takes into account axial vessel movement. One of the major limitations is that the surgical procedure to expose the vessel could modify the genuine elastic properties of the vessel wall, even if carefully attention was paid not to severe the adventitia. Another limitation of the experiment is the flowmeter with a maximal sensitivity of 1 ml/min [7]. We tried to reduce the technical error by switching the probes into the inflow and outflow position three times per animal. Even with many limitations, this method has the prerogative of being able to quantify the impact of axial strain in calculations of compliance. Our results correlate with those reported in current literature from the qualitative point of view: as blood pressure increases, φ decreases instantaneously (Figure 3) and therefore, C_d decreases [9]. The impact of axial strain in compliance calculations results in measurements of C_d being smaller than CC because in the equation ΔV/ΔP = (L × CC) + A × ΔL/ΔP (*4*) the A × ΔL/ΔP <0, since vessel shortens when pressure increases. Thus, DV/DP < (L × CC) which means that dynamic arterial compliance is smaller than cross-sectional compliance. Assuming L = 1 μm, we can state that C_d is one order of magnitude smaller than traditionally calculated CC (10^{-7} vs 10^{-8}). We can speculate that for the same pulse pressure, the increase in vessel diameter is proportional to the decrease in vessel length and vice-versa. There is probably a correlation between the degree of diameter changes and the degree of shortening, ie, the greater the diameter increase, the greater the axial shortening. Therefore, vessel volume variations (ΔV) during the cardiac cycle are smaller than previously thought.

If these results are confirmed by more exten-

sive studies, then reappraisal of all clinical strategies based on arterial compliance evaluation would appear to be necessary.

Conclusions

Cross-sectional compliance provides a limited approximation of the real phenomenon because it neglects the longitudinal vessel movement. Our approach takes into account the volume changes over time which result in an improved description of the real compliance. Dynamic compliance is one order of magnitude smaller than traditionally calculated CC because vessel volume changes during the cardiac cycle are smaller than previously thought. However, further investigations are necessary to explore this issue.

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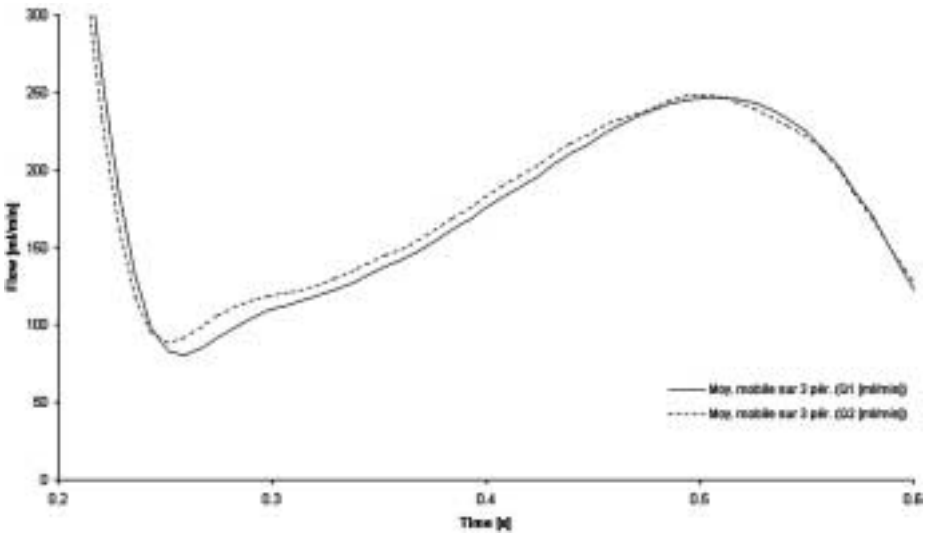

Figure 3

Inflow (dash line) and outflow (continuous line) through a 10 cm segment of pig carotid artery acquired simultaneously. The difference between the two lines is the phase shift (φ) and it represents the energy converted in the vessel wall deformation during blood displacement.

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