34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Simulation of reduction of proximal aortic stiffness by an elastic wrap and effects on pulse pressure

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Abstract— **Aortic stiffness is a major cause of age-related increase in arterial pulse pressure (PP) and associated increase in work load for the heart. A method to treat this condition is proposed: wrapping the ascending aortic wall with a highly compliant elastic material such that reducing the vessel diameter will shift the pulsatile load from the aortic wall to the wrap, thus increasing the functional compliance of the ascending aorta and decreasing the cardiac load. A multibranched mathematical model of the arterial system, in which every segment of the arterial tree is represented as a uniform elastic circular tube, has been used to simulate the effect of the wrapping procedure on PP and impedance changes, by varying the radius (R) and the stiffness (E) of the ascending aortic segment. The results of the simulation show that PP decreases with an increase in R and a decrease in E. A similar trend, but with a different sensitivity, is observed for the characteristic impedance (Z_c) changes. The model shows that PP in the ascending aorta can be lowered by 8.8% by reducing R of 20% and decreasing the functional E by 80%, in good agreement with preliminary results obtained from an *in vitro* pilot study of elastic wrap in aortas. In conclusion, the modelling study demonstrates that the proposed aortic wrapping procedure is able to compensate for the increase in PP associated with R reduction by a decrease in PP determined by a reduction in functional E. Therefore, it supports the use of the aortic wrap as a potential non-pharmacological treatment of age-related increase in PP.**

I. BACKGROUND

Age-related increase in arterial stiffness is determined by changes in the aortic wall properties including stretching and fragmentation of the elastic lamellae within the vessel wall, caused by the repetitive cyclic stresses induced by the heart pulsations on the arterial walls [1].

In particular, stiffening of the ascending aorta with aging is a major determinant of hypertension and cardiac failure, because of its fundamental role in the arterial "windkessel" function, converting the pulsatile flow from the heart into a more steady flow in the peripheral vasculature. The ascending aorta, rich in elastin content, buffers the ventricular stroke during systolic expansion, and functions as a reservoir to distribute blood flow during diastolic relaxation. Therefore, a decrease in compliance of this arterial segment, which accounts for about 60% of the total systemic compliance [2], causes an increase of systemic input impedance (Z_{in}) and characteristic impedance (Z_c) and increases pulse wave velocity with associated early wave reflection. All these factors contribute in raising aortic pulse pressure (PP), with subsequent onset of hypertension and increase of left ventricular work, which in turn leads to cardiac hypertrophy, higher myocardial metabolic requirements, and potentially heart failure. The increased pulsatile pressure further damages the vascular elastic structure of the arterial wall, leading to further increase in aortic stiffness, in a positive feedback mechanism [3].

Current treatments of heart failure aim to reduce cardiac load, either pharmacologically, by reducing the arterial peripheral resistance, or mechanically, by intra-aortic balloon counterpulsation and ventricular assist devices.

As described in a recent study by Ioannou *et al.,* acute reduction of aortic compliance determines an increase in Z_{in} and Z_c, with a subsequent increase in systolic pressure (SP) and PP, leading to cardiac hypertrophy [4]. If, on the contrary, aortic compliance is increased (i.e. stiffness is decreased), inverse results are expected: decreased SP and PP, reduction of Z_{in} and Z_c, and reduced ventricular work.

A proposed method to obtain these effects is the aortic wrapping procedure: a wrap made of an elastic material applied around the ascending aortic segment, reducing the aortic diameter to values similar to those observed in young healthy adults [5]. We hypothesize that, after wrapping, the pulsatile load will be borne by the external elastic wrap rather than the aortic wall, thus reducing the functional stiffness of the vessel. The procedure will therefore lower SP, improving ventricular ejection and decreasing the myocardial oxygen demand, while it will increase diastolic pressure, improving myocardial blood flow. In summary, this procedure is expected to lower PP and the pulsatile external work by the heart, thus increasing the efficiency of the circulation.

In this study, a mathematical model of the arterial circulation has been used to evaluate the effects of the aortic wrap on PP at the aortic root. In an *in vitro* pilot study performed by Iliopoulos on excised aged human aortas connected to a mock hydraulic circuit, wrapping the ascending aorta reduced R to about 80% of the baseline value, the measured functional E of the segment being approximately 20% of the stiffness of the unwrapped native vessel [6]. For this reason, special attention has been placed

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on this specific scenario (80% R and 20% E) when analyzing the data of the simulation.

II. METHODS

A mathematical, multi-segment model of the arterial circulation has been used to investigate the effects of compliance and diameter changes on PP in the ascending aorta. The work of Avolio [7] forms the basis of the model used.

The current model consists of 136 segments and 76 nodes, describing the anatomical branching of the arterial tree. Each segment represents one arterial section as a uniform circular thin-walled elastic tube, with internal elastic, viscous, and inertial properties, which are described in terms of the tube physical properties: length, wall thickness, radius (R), Young's modulus (E), Poisson ratio, wall viscoelasticity, blood density, and blood viscosity. The values chosen for all parameters were typical of elderly subjects, and are derived from the literature and anatomical atlases [8] [9]. The model calculates the characteristic impedance of each segment (Z_o) from the closed-form solutions of the Navier-Stokes equations for pulsatile flow in elastic tubes (as described by Womersley [10]) and the Moens-Korteweg equation for wave velocity. The viscoelastic properties of the arterial wall are described by the tangent of the angle φ, representing the phase lead of pressure in relation to wall displacement. Values of resistance, Z_{in}, transmission ratio for each segment are calculated by means of electrical transmission line theory. Pressure can then be determined at any node throughout the arterial tree for a given flow input at the aortic root. Calculations are performed with a constant ventricular ejection wave with maximum velocity of 66 cm/sec, systolic ejection period of 490 msec and cardiac cycle length of 830 msec. The ejection wave was typical of an old subject [1].

The effect of variations in elastic properties and geometrical features were then determined. In particular, the wrapping procedure was simulated by incrementally varying E and R of the ascending aortic segment, and the subsequent changes in PP and impedance were calculated at the aortic root.

The model and the post-processing of the results were run in Matlab 7.12.0 (The Mathworks Inc., Natick, MA).

III. RESULTS

The results presented show the calculated values of PP, SP, Z_c, and Z_{in} at the aortic root (first segment of the model), when values of R and E are incremented in the central part of the ascending aorta (second segment of the model).

All variable values are normalized, calculated as percent of the respective variable reference values (relative to a control condition in which R and E are unchanged). The reference values are expressed with the termination "100" (PP100, SP100, Z_c100, Z_{in}100, E100, R100).

E varies from 5% to 195% of E100 in 30 increments of 5%, while R varies from 50% to 150% of R100 in 10 increments of 10%.

A 3D mesh plot of the calculated PP changes vs. the total range of R and E variations is presented (fig.1). PP increases when R is reduced, whereas an inverse pattern is observed for the E variations. Moreover, the sensitivity of PP changes, for every R value, is higher for E values <20%E100, compared to the symmetric situation of E values >180%E100, where instead the PP curves reach a plateau.

Changes in Z_c vs. variations of E and R are shown in a 3D mesh plot (fig.2). Similarly to the PP trend, an increase in Z_c is observed for R reduction and for E augmentation, but the sensitivity of the curve is higher for smaller R (<70%) for every E value.

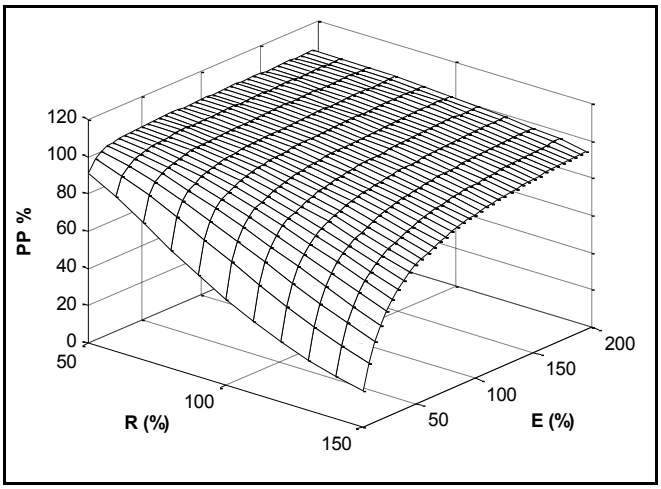

Figure 1. PP (as % of PP100) calculated by the model for the aortic root vs. variations in R (as % of R100) and E (as % of E100) of the ascending aortic segment.

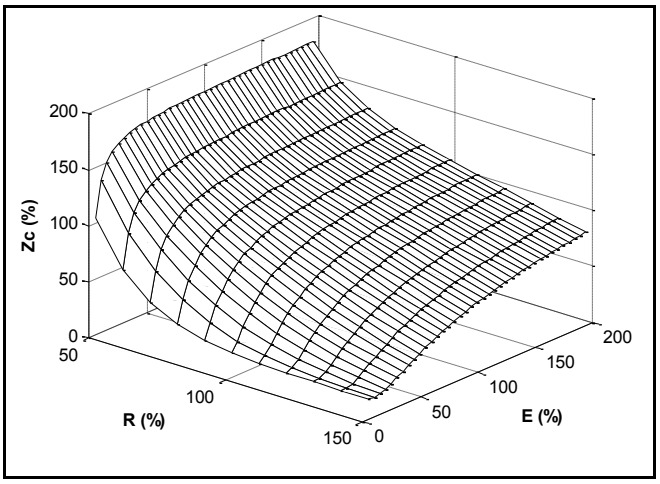

Figure 2. Z_c (as % of Z_c100) calcultated by the model for the aortic root vs. variations in R (as % of R100) and E (as % of E100) of the ascending aortic segment.

The Z_{in} modulus is plotted for the first 20 harmonics (fig.3). Two different scenarios are described: the baseline scenario (solid line), in which there is no variation of R and E, and the "realistic" wrapped scenario (dotted line), in which values of R (80% R100) and E (20% E100) are chosen, as expected to occur after the wrapping procedure

according to the *in vitro* pilot study results. The values of Z_{in} are normalized to the value of the baseline impedance at the first harmonic. A decrease in Z_{in} is observed for the wrapped scenario at every harmonic component.

In summary, the changes in PP, SP, and Z_c are shown in table I, for the R and E variation ranges expected to occur in a real surgical wrapping procedure. As shown by the table, for an R value of 80%R100, an E value of 20%E100 is needed to achieve a drop in PP to a value of 91.2%PP100, corresponding to a SP of 89.4%SP100 and a Z_c of 78.4%Z_c100.

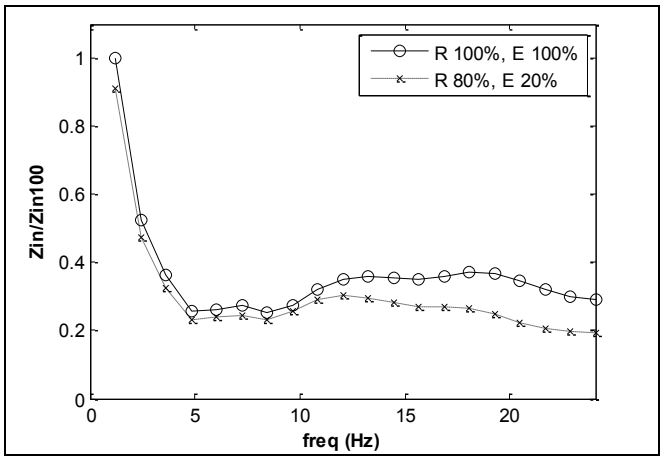

Figure 3. Modulus of Z_{in} calculated by the model at the aortic root, when no variations are imposed (R = 100% R100, E = 100% E100, solid line) and for variations that simulate what is expected to occur after wrapping (R = 80% R100, E = 20% E100, dotted line).

TABLE I. CHANGES IN PRESURE (PP AND SP) AND IMPEDANCE (Z_C) VALUES IN THE ASCENDING AORTA, INDUCED BY SIX VARIATIONS OF E AND TWO VARIATIONS R

E%	PP%		SP%		Zc%	
	R 100%	*R 80%*	*R 100%*	*R 80%*	*R 100%*	*R 80%*
5	45.6	63.5	40.0	58.0	21.8	32.3
10	64.3	79.8	58.8	75.7	30.0	51.7
15	74.2	87.1	69.4	84.3	40.4	67.3
20	80.4	91.2	76.3	89.4	50.0	78.4
25	84.5	93. 9	81.2	92.7	58.0	86.4
30	87.6	95.7	84.7	95.1	64.7	92.4

All values calculated as % of the respective reference values (PP100, SP100, Zc100, E100, R100)

IV. DISCUSSION

The mathematical model described was used in this study to simulate the changes in PP, SP, and Z_c at the aortic root determined by incremental variations of R and E of the ascending aortic wall. In particular, it was used to predict the effects on pressure and impedance of the proposed aortic wrapping procedure, which can be represented by reduced R and E.

Results show that the effect of PP reduction associated with a decrease in functional stiffness of the wrapped aortic segment is able to override the increase in PP associated with a reduction in radius. That is, the model predicts that if the ascending aorta is wrapped and its radius is reduced by 20% (R = 80%R100), a reduction in functional stiffness by 80% (E = 20%E100) is required to induce a drop in PP by 8.8%.

The model results are in good agreement with values measured during the *in vitro* pilot study (described in section I) in which human aged aortas were connected to a pulsatile flow pump in a mock hydraulic circuit [6]; the aortas (n=9) were wrapped with two different wraps made of materials with different stiffness (material A, characterized by 4% increase in diameter with each pulsation, and material B, characterized by a 12% increase), and the radius of the wrapped segment was set to three different R values (91%, 82%, and 70% of the baseline values). To allow for a comparison between the *in vitro* and modelled data, four 2D projections of the modelled 3D surface described in fig. 1 are plotted on the PP-E plane for four different values of R variation (70%, 80%, 90%, and 100% of R100), chosen as the closest values to the experimental R values (fig.4). On the same graph, six data points are plotted with different geometrical markers, corresponding to six different in vitro experimental set-ups (three different R values and two different wrap materials), whose values are averaged for the 9 samples. As shown by the graph, the two data points relative to R reduction of 30% (R = 70%) fit on the relative calculated curve. The four experimental set-ups relative to R reductions of 18% and 9% instead correspond to values of PP which are slightly underestimated by the mathematical model.

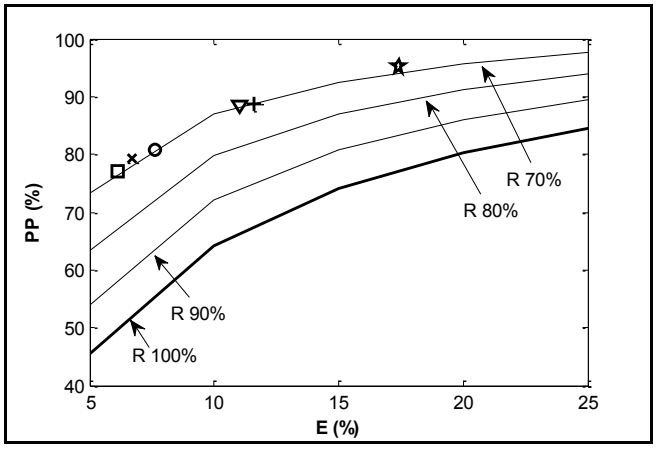

Figure 4. Solid lines represent PP calculated by the model (as % of PP100) at the aortic root, vs. E variations (as % of E100) of the ascending aortic segment, for four different R variations (100%, 90%, 80%, and 70% of R100). Six data points measured in the *in vitro* pilot study are plotted over the model lines with the following markers: star (material B, R= 91% R100), triangle (material A, R= 91% R100), plus sign (material B, R= 82% R100), circle (material A, R= 82% R100), x sign (material B, R= 70% R100), square (material A, R= 70% R100).

In conclusion, the predicted values of PP reduction and the cardiac unloading suggested by the reduction of Z_c, for realistic values of R and E reduction achievable by aortic

wrapping, could be beneficial in the treatment of hypertension and cardiac failure. The modeling findings, supported by the pilot *in vitro* results, indicate the aortic wrapping procedure as a promising non-pharmacological hypertension treatment, whose efficacy needs to be further investigated.

ACKNOWLEDGMENT

Francesca Giudici is supported by the International Macquarie University Research Excellence Scholarship (iMQRES). The authors wish to acknowledge the contributions by Dr Jim Iliopoulos for the *in vitro* experimental data, and by Dr Koen Matthys for the adaptation of the model to Matlab code.

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