Local Indices of Aortic Stiffness
A Magnetic Resonance Imaging Study

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Abstract

The stiffness of the aortic wall was evaluated by coupling the morphological and the blood flow MR data. The deformability of the ascending aorta, and the aortic Pulse Wave Velocity (PWV) were estimated in a series of 36 volunteers aged between 14 and 77 years. An accurate automatic method of segmentation for extracting contours of the aorta was used. A 3D estimation of the length of the aortic arch and a precise measurement of the transit time between ascending and descending flow waves were performed. Results. The deformability and the PWV were inversely related. Mean ± SD values of deformability and PWV for the younger subjects (age<50) were respectively 0.25±0.11 and 4.03±0.83m/s. For the older subjects (age≥50) they were 0.068±0.04 and 7.01±1.14m/s. Conclusions. The local and automated approach for measurement of deformability and PWV characterizes directly the stiffness of the aorta and results are consistent with previous studies.

1. Introduction

Magnetic resonance imaging (MRI) is increasingly used for the analysis of mechanical properties of the aortic wall and blood flow patterns [1-3]. Elastic properties of the aortic wall are an independent predictor of cardiovascular mortality [4]. A number of indexes, including deformability and aortic pulse wave velocity (PWV), can be assessed directly and non-invasively with MRI. Several studies used the aortic deformability and the aortic PWV to characterize the aortic stiffness [1,5,6,7]. The aortic deformability describes the ability of the aorta to expand during systole, it decreases in stiffer arteries. The PWV is the speed of the pulse wave travelling along the arteries during each cardiac cycle. It is related to the elasticity of the vessel wall, it increases in stiff arteries. The aim of this study was to measure the deformability and the PWV by coupling the morphological and the hemodynamic MR data. To

achieve this aim, an accurate automatic method of segmentation of the vascular lumen was used for extracting the contours of the aorta on the cine and phase contrast (PC) MR data. To measure the PWV, a method which provides a 3D estimation of the length of the aortic arch and a precise measurement of the transit time between flow waves was implemented. A comparison between obtained deformability and PWV results was performed. As aging is an accepted factor of cardiovascular risk and is associated with a number of deleterious changes in cardiovascular system [8,9], we also studied the variation of the deformability and the PWV according to aging.

2. Methods

MRI Acquisitions

A total of 36 volunteers with no referenced cardiovascular trouble, aged between 14 and 77 years were recruited in the study. All examinations were performed on a 1.5 Tesla scanner (Sigma LX; General Electric Medical Systems, Milwaukee, Wis). Phase contrast (PC) and cine image sequences were acquired for each subject. For the PWV study, the PC slice was set perpendicular to the axis of the aorta at the level of the bifurcation of the pulmonary trunk. Hence, the ascending and descending aorta could be studied simultaneously. The data were acquired using an ECG-gated gradient sequence with a velocity encoding gradient in the through plane direction. This pulse sequence generates phase-related pairs of modulus and velocity-encoded images: inter phase duration varied between 38 ms and 16 ms, pixel size ranged between 1.25×1.25mm² and 1.72×1.72mm² and slice thickness was 8mm. For the deformability study, axial cine slices were acquired using an ECG-gated cine FIESTA-SP sequence: inter phase duration varied between 62 ms and 21 ms, pixel size ranged between 0.68×0.68mm² and 0.78×0.78mm² and slice thickness was 8mm. The data were recorded at the

same level as for the PC slices. With the same sequence, axial and coronal sequences were also recorded at different levels of the aorta covering the whole aortic arch for further evaluation of the geometry of the aorta.

Image Analysis

Algorithms for image analysis were developed and integrated into the specialized software "ART Fun" [10].

Assessment of the deformability. The aortic deformability is defined as the change in the cross sectional area during a cardiac cycle. It is calculated as the ratio between the variation in the area of the aortic lumens between systole (Ss) and diastole (Sd) and the diastolic area Deformability=(Ss-Sd)/Sd. These areas were measured on cine MR acquisitions using a (2D+t) snake based automatic contouring. This automatic method to detect aortic contour on each image gives a cross sectional area versus time curves (Figure 1). The systolic and diastolic surfaces were defined respectively as the maximal and the minimal areas of the curves.

Extraction of flow wave curves. Aortic contours of the ascending and descending aorta were derived automatically from the modulus images of all cardiac phases using the (2D+t) snake based automatic contouring. These contours defined regions of interest (ROIs) that were reported on each velocity encoded image. The mean velocity value was calculated in each ROI. Thus, a mean velocity waveform versus time was generated for both ascending and descending aorta (Figure 2.a).
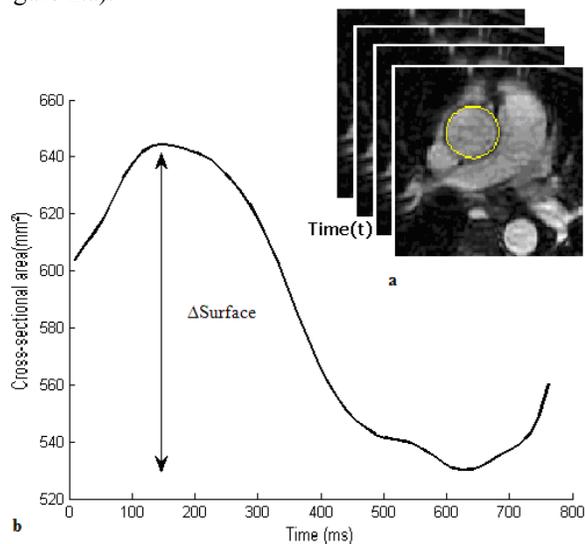
Assessment of aortic pulse wave velocity. The PWV was calculated as the ratio of the distance between ascending and descending aorta (d) and the time difference (dt) between the arrival of the velocity wave at these levels PWV=d/dt. The 3D length of the aorta (d) was calculated from axial and coronal spin echo slices (cine MR acquisitions). The centre of the lumen was selected by an experienced user on each slice. The selected points were interpolated using a 3D cardinal spline. The length of this 3D curve provided the total length of the aortic arch between the ascending aorta at the level of the pulmonary trunk and the descending aorta at the same level (Figure 2.b). Transit time (dt) was calculated automatically, using an algorithm based on the least squares minimization of the normalized mean velocity waveforms of the ascending and descending aorta. The method of least squares gives the transit time for which the resemblance between the profile of the flow waveforms at the levels of ascending and descending aorta is maximal. The systolic up-slope of the mean velocity waveforms were considered in this procedure.
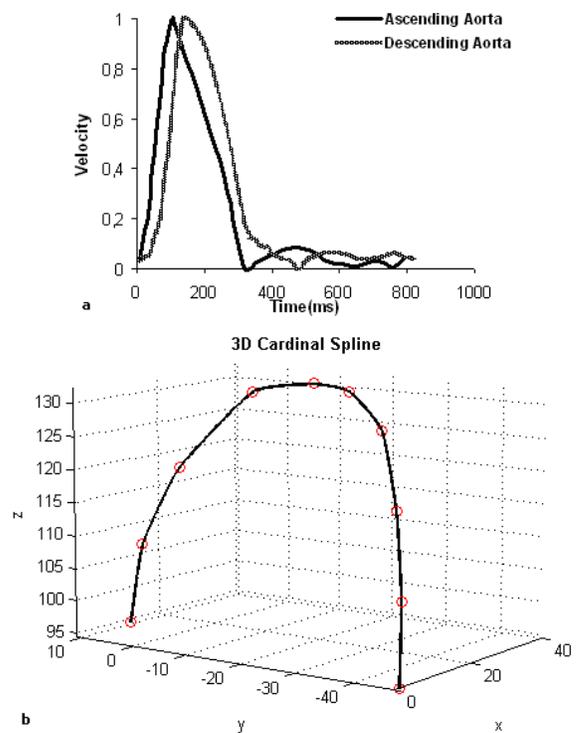

Figure 2. Study of the pulse wave velocity. a: Estimation of the transit time between the ascending front of the mean velocity waveform at the level of ascending and descending aorta. b: Estimation of the length of the aorta from axial and coronal slices with a 3D cardinal spline interpolation.

Figure 1.Determinaton of the aorta cross sectional area during a cardiac cycle. a: Automatic contouring of the ascending aorta. b: Ascending aorta cross sectional area versus time curve.

Statistical Analysis

The aortic deformability of the ascending aorta and the PWV were calculated for each subject. First, the variations of these local indices were compared between themselves: by plotting deformability versus PWV. Second, the relationship of each index according to the age was analysed: plots of results versus age were performed. The comparison was studied using regression analysis and the mean +/- standard deviation (SD).
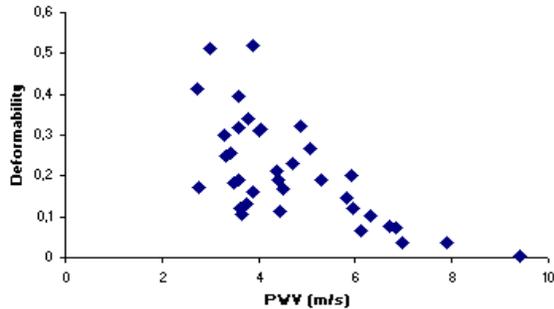

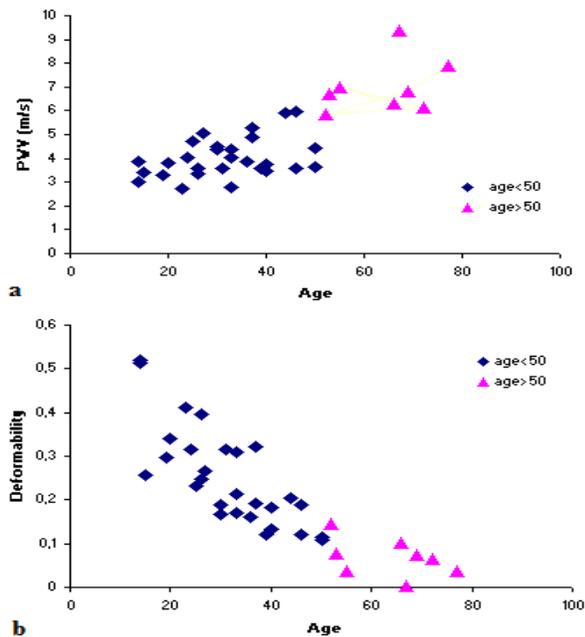Figure 3. Plot of deformability versus PWV.

Figure 4. Variations of deformability and PWV with age. a: PWV versus age. b: Deformability versus age.

3.   Results

Figure 3 shows the relationship between the deformability and the PWV. The deformability and the PWV were inversely related: decrease in deformability corresponded to increase in PWV.

Figure 4 shows the variation of deformability and PWV according to aging. Both relationships were non

linear and were better characterized with a second order polynomial regression: age-PWV $r^2=0.64$ / age-deformability: $r^2=0.75$. (Linear regression: age-PWV $r^2=0.61$ / age-deformability: $r^2=0.69$).

Subjects with age < 50 years were clearly identified: they had a PWV< 6m/s (mean 4.03 m/s, SD 0.83m/s) and a value of deformability > 0.1 (mean 0.25, SD 0.11). The volunteers with age ≥ 50 years had a value of PWV >5.8 m/s (mean 7.01 m/s, SD 1.14m/s) and a value of deformability <0.2 (mean 0.068, SD 0.04). Only one had a value of PWV<6m/s and a value of deformability>0.1.

In addition, the changes in PWV were more marked in older subjects (≥50 years) compared with younger subjects, whereas the age related changes in the deformability were more pronounced in younger subjects (age<50 years).

4.   Discussion and conclusions

The indices of the deformability and the PWV were easily assessed non-invasively using MRI. The deformability is a local index of aortic stiffness, whereas the PWV is a regional index. Our results showed that deformability and PWV gave the same description of the stiffness of the aortic wall.

For the deformability study, the systolic and the diastolic areas were measured on the axial cine acquisitions using a snake based automatic contouring. To take into account the difficulties of segmentation mostly related to intensity variations over the cardiac cycle, our technique included specific features: 1) to reduce variations in intensity within the aortic lumen during the cardiac cycle, the intensity was automatically scaled and 2) to consider the coherence of the aortic wall motion during the cardiac cycle, the aortic contour was modelled by a 2D+t deformable surface (x, y, t). This processing allows an automatic determination of the aortic deformability, avoiding manual tracing that could be time consuming and could induce significant inter and intra observer variability. We applied the same algorithm of segmentation on the PC acquisitions for extracting the mean flow values in the ascending and descending aorta.

For the PWV study, similar methods using MRI have previously been described [1,2,3,7]. The principal difference with the proposed methods was the determination of the transit time. Many authors used the "foot-to-foot" method, they calculated the transit time as the delay between the feet of the two flow waves corresponding to the upslope of the flow waves at the beginning of the systole [3,7]. Groenink [2] measured the transit time between the two points where the flow reached half of its maximum value. Lalande [11] used the method of least squares to calculate the transit time and considered the whole shape of the two flow curves. The automatic matching between the systolic up-slope profile

of the two curves using a least squares minimization avoids the restriction of the analysis to a few points of the curves, and to minimize the variability of foot-to-foot measurement due to the low temporal resolution on flow curves. We have chosen to match the systolic up-slope profile to avoid the descending front of the profile which can overestimate the flow due to a possible early reflection wave. We considered the flow wave unidirectional and reflectionless between the onset of the blood flow and the time of its maximum [7]. The length of the aortic arch was generally measured manually as the centreline of the aorta on the sagittal image in the plane of the aortic arch. In our work, the aortic distances were measured through the centres of the aorta lumen selected on both the coronal and axial slices. The sagittal acquisitions give a 2D section of the aorta, however due to the 3D geometry of the aorta; the set of centres of the aorta lumen cannot be precisely extracted from this 2D plane. Thus, it is not possible to select precisely the centre of the aorta lumen using a single sagittal slice. Our technique gives a more precise measurement of the distance. PWV values obtained in our study in young subjects were consistent with values proposed in other MRI studies.

Age is considered as an important determinant of cardiovascular risk. In some previous works [2,3], changes in aortic PWV according to the age were studied and the authors suggested that PWV increased with age according to a linear variation. In the present work, PWV increased according to the age but changes did not appear linear. The variation was much better represented with second order polynomial than with a simple linear regression. In addition, the changes of the PWV were more marked in older subjects (> 50years). These results are in good agreement with previous work of Carmel [8]. In contrast to PWV, the deformability decreased according to the age and this decrease was more marked in younger subject (<50 years). The age related change was also better represented with second order polynomial. In this study, the younger subjects (<50 years) have the lowest PWV and the highest deformability. A value of 0.10 and 6m/s can be defined as a threshold of the aortic deformability and PWV between the younger subjects (<50 years) and the older subjects (> 50 years).

In conclusion, we evaluated non-invasively the stiffness of the aortic wall from morphological and hemodynamic MR data. We described a local and automated technique for measurement of deformability and PWV. This technique characterises directly the stiffness of the aorta. The local indices of deformability and the regional indices of the PWV were independently measured on the aorta, however they were well related. Aging has a significant influence on the aortic stiffness;

the older subjects (> 50 years) have the highest PWV and the lowest deformability. Importantly, age related changes in PWV were more marked in older subject whereas deformability decreased significantly in younger subjects.

References

[1] Groenink M, de Roos A, Mulder BJ, Spaan JA, Van der Wall EE. Changes in aortic distensibility and pulse wave velocity assessed with magnetic resonance imaging following beta-blocker therapy in the Marfan syndrome. Am J Cardiol 1998;82:203–208

[2] Groenink M, de Roos A, Mulder BJ, et al. Biophysical properties of the normal-sized aorta in patients with marfan syndrome: evaluation with MR flow mapping. Radiology 2001;219:535–540

[3] Mohiaddin RH, Firmin DN, Longmore DB. Age-related changes of human aortic flow wave velocity measured noninvasively by magnetic resonance imaging. J Appl Physiol 1993;74:492–497

[4] Laurent S, Boutouyrie P, Asmar R, et al. Aortic stiffness is an independent predictor of all-cause and cardiovascular mortality in hypertensive patients. Hypertension 2001;37:1236–41

[5] Mohiaddin RH, Firmin DN, Longmore DB. Age-related changes of human aortic flow wave velocity measured non invasively by magnetic resonance imaging. J Appl Physiol 1993;74:492–497

[6] Laffon E, Marthan R, Montaudon M, Latrabe V, Laurent F, Ducassou D. Feasibility of aortic pulse pressure and pressure wave velocity MRI measurement in young adults. J Magn Reson Imaging 2005;21:53–58

[7] Vulliemoz S, Stergiopulos N, Meuli R. Estimation of local aortic elastic properties with MRI. Magn Reson Med 2002;47:649–654

[8] Carmel M, Yasmin , Ian R,Qasem A,Ian B Wilkinson,John R . Normal Vascular Aging:Differential Affects on Wave Reflection and Aortic Pulse Wave Velocity. J American College Cardiology 2005 ;46:1753-1760

[9] Alecu C, Labat C,Kearney-Schwartz A, Fay R, Salvi P, Joly L, Lacolley P, Vespignani H, Benetos A. Reference values of Aortic Pulse Wave Velocity in the Elderly.J Hypertens 2008;26:2207-12

[10] De Cesare A, Redheuil A, Dogui A, Engineer OJ, Lalande A, Frouin F, Mousseaux E, Herment A."ART-FUN": an integrated software for functional analysis of the aorta Journal of Cardiovascular Magnetic Resonance 2009;11:182

[11] Lalande A,Khu Van Kien P,Walker P M,Zhu L,Legrand L, Claustres M, Jeunemitre X, Brunotte F,Wolf J E.Compliance and Pule Wave Velocity Assesed by MRI Detect Early Aortic Impairment in Young Patients With Muttion of the Smooth Muscle Myosin Heavy Chain. J Magn Reson Imaging2008;28:1180-1187

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