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Quantitative Indicator of Abdominal Aortic Aneurysm Rupture Risk Based on its Geometric Parameters

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***Abstract*—**Abdominal aortic aneurysms rupture (AAAs) is one of the main causes of death in the world. This is a very complex phenomenon that usually occurs "without previous warning". Currently, criteria to assess the aneurysm rupture risk (peak diameter and growth rate) can not be considered as reliable indicators. In a first approach, the main geometric parameters of aneurysms have been linked into five biomechanical factors. These are combined to obtain a dimensionless rupture risk index, RI(t), which has been validated preliminarily with a clinical case and others from literature. This quantitative indicator is easy to understand, it allows estimating the aneurysms rupture risks and it is expected to be able to identify the one in aneurysm whose peak diameter is less than the threshold value. Based on initial results, a broader study has begun with twelve patients from the Clinic Hospital of Valladolid-Spain, which are submitted to periodic follow-up examinations.

***Keywords*—**AAA, Rupture risk prediction, Biomechanical factors, AAA geometric characterization.

I. Introduction

ABDOMINAL aortic aneurysm (AAA) is defined as a localized, progressive and permanent dilatation (usually larger than 3 cm in diameter) of the aorta. At present, its statistics are of great concern. The age span in which it may appear, and the number of cases is increasing. As a consequence, the social and economic costs associated with the medical treatments and patients recovery are very high.

Nowadays, the maximum transverse diameter and the expansion rate of the AAA are the criteria used to predict the development and the rupture risk of an aneurysm, defining the treatment to be followed by the patients. They are kept under observation if the peak diameter is less than a statistics based threshold (5-5.5 cm) and otherwise they are submitted to periodic follow-up examinations. These also occur when small aneurysm (< 5 cm in diameter) are expanding at a large rate: 0.5-1 cm/year.

However, the rupture phenomenon is much more complex and these factors, though important, can not be considered as a reliable determinant of AAA rupture because they do not consider other important factors. Indeed it has been demonstrated, by clinical evidence and numerical and/or experimental studies, that small aneurysms (<5 cm) can rupture, with serious consequences for patients.

Hence, in last years researchers and physicians have had the challenge to identify when an aneurysm, regardless of its size, is in danger of rupture in order to determine the appropriate treatment. In this sense, some individual and biomechanical factors have been defined so as to assess when the aneurysm is close from rupture. These factors are summarized in [2] and [7].

The biomechanical factors (BFs) are defined as functional relations between biological, geometrical and/or mechanical factors defining the general state of the aneurysm and characterizing its evolution from a quantitative point of view. Among these factors the ones related with aneurysm geometry, which can be easily determined with the information obtained from a CT images set, are the ones to describe the arterial deformation and therefore, allows characterizing its real development stage. Hence, the considered hypothesis for an adequate and accurate study about geometric biomechanical factors (GBFs) identifies a simple and reliable indicator of the rupture risk, improving the current medical criteria.

This work present a theoretical foundation and a preliminary study about the possibilities to define a quantitative indicator to estimate the development state of an AAA and its rupture risk through functional relations between its geometric parameters in a quick, accurate and patient-specific way.

II. Method Grounds

A novel approach to assess the rupture risk in aneurysm, is presented by [2]. The authors combined biological, geometrical and "mechanical" factors to obtain a dimensionless severity parameter, from which they could estimate, the potential risk of a specific aneurysm in any stage of development.

In the present paper, this concept has been modified to consider only the main geometric parameters of the aneurysm which can be determined by CT or MRI images set during

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periodic check-up. The basic idea is that these geometric parameters define the AAA from a geometric point of view. Fig. 1 shows an AAA schematic representation where the main geometric parameters involved in the method are defined. D is the peak diameter (DA in actual state, DP in previous state), d is the non-deformed aorta diameter, L is the aneurysm length which is measured from proximal neck to distal neck, la is the anterior length measured from point of intersection O to anterior wall and lp is the posterior length measured from point of intersection O to posterior wall, and t is the thickness of the AAA wall.

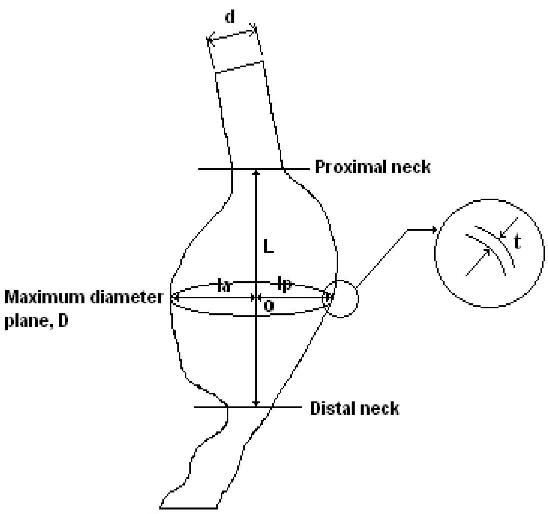

Fig. 1 AAA schematic representation with its main geometric parameters

These parameters have been adequately combined to define the proposed geometric biomechanical factors (GBFs). Some considerations about them are listed below:

1) *Deformation Rate, χ.* Characterizes the actual deformation of the aorta, therefore it constitutes a relation between the aorta diameter, d (included between 1.5 and 2.5 cm for any patient), and the maximum diameter of the aneurysm, D. The value that defines a low rupture risk is taken as the lower deformation condition of the artery (lower D and higher d), and for the most critical condition, as the higher deformation (higher D and lower.
2) *Asymmetry, β.* A characteristic feature of an aneurysm is its asymmetry, which can be attributed to the non-symmetry expansion of the aneurysm sac as a result of the expansion constraints introduced by the proximity to the spinal column [4]. Due to this, AAA geometry exhibits a high surface complexity and a significant tortuosity of the inflow conduit and the segments of the iliac arteries. An aneurysm has lower rupture risk if it is more symmetric ($\beta = 1$) and the risk increases as lp tends to be lower than la.
3) *Saccular Index, γ.* This factor assesses the length (L) of the AAA region, which is the region, affected by the formation and further development of the aneurysm. This means that long aneurysms have more rupture possibilities than a short one. Typical values of L are ranged from 40 to 83 mm (in some works this value is specified higher). The calculation condition of the upper threshold value is the higher value of L and the peak value of D (typical for elective repair).
4) *Relative Thickness, ι.* The aneurysm geometric characterization determines the existence of a variable wall thickness, both between the anterior and posterior walls and between the aneurysmatic sac and the regions close to the distal and proximal ends. According to [6], typical values of wall thickness (t) in aneurysmatic arteries are ranged from 0.5 to 1.5 mm. The danger of aneurysm rupture will be greater when the thickness is low in the peak diameter region. This trend falls with the increase of the wall thickness.
5) *Growth rate, ε.* It is considered as an important indicator for AAA rupture. A high expansion rate of 0.5-1.0 cm/year is often associated with a high risk of rupture, and an elective repair should be considered even if the maximum diameter is lower than 5 cm. The value indicating that an aneurysm is in rupture risk has been determined regarding to the worst situation (the lowest value inside the range of high growth rate (0.5cm/year), the peak diameter D and the time T between periodic check-up (0.5 year). The low rupture risk limits were determined for aneurysm formation conditions.

Once these factors are defined, it is necessary to evaluate their weight in the rupture phenomenon. The value of each GBF is sorted in an interval which is linked with a weighted level risk WLRi. Moreover each of the GBFi have their own weighted coefficient ωi. The weight of each factors and interval has been calculated by statistical analysis. The WLRi have been obtained from considerations made in open literature when the importance of a factor's value is given according to the level of risk. The coefficients ωi have been obtained from the opinion of a group of surgeons about the importance of each factor.

Hence, rupture risk qualitative indicator can be expressed as the sum of each weighted coefficient ωi multiplied by the corresponding WLRi:

$$RI(t) = \sum_{i=1}^{5} \omega_i WLR_i \qquad (1)$$

Regarding the results of RI(t), it is possible to advise several actions and suggestions to physicians. In this initial stage of definition, the data suggested in [2] have been utilized, what seems to be appropriate. When RI(t) <0.2, the rupture risk is very low and no action is suggested. When the risk index is ranged from 0.2 to 0.45, the rupture risk is low and a close observation is required. If RI(t) is greater than 0.45, elective repair should be considered by physicians, observing other symptoms such as back and abdominal pain, syncope or vomiting. When RI(t)>0.7, the rupture risk is very high and the surgical intervention should be necessary.

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TABLE I
GEOMETRIC BIOMECHANICAL FACTORS CHARACTERIZATION

GBF	Definition	Threshold values				Weighted Coefficient, ω_i
		Low Risk	Middle Risk	High Risk	Dangerous	
Deformation Rate, χ	$\frac{D}{d}$	1.20-1.70	1.71-2.30	2.31-3.29	≥3.3	0.35
Asymmetry, β	$\frac{D-l_a}{l_a}$	1-0.9	0.8-0.7	0.6-0.5	≤0.4	0.10
Saccular Index, γ	$\frac{D}{L}$	≥0.75	0.74-0.69	0.68-0.61	≤0.6	0.10
Relative Thickness, ι	$\frac{t}{D}$	0.05-0.042	0.041-0.025	0.024-0.011	≤0.01	0.20
Growth rate, ε	$\frac{(D_A - D_P)}{T}$	0.1-0.17	0.18-0.3	0.31-0.49	≥0.5	0.25
Weighted Level Risk, WLR_i		0.1	0.3	0.7	1	

Table I shows the threshold values assigned to each geometric biomechanical factor and their related weighted coefficient and level risk.

From analysis of the AAA geometric characterization, other GBFs could be defined, i.e. AAA/ILT area, tortuosity, wall curvature, etc. but they are determined through more complex procedures, so they are not considered in the present study to evaluate the quantitative indicator definition.

III. RESULTS AND DISCUSIONS

The rupture index (RI(t)) is defined to monitor the evolution of patients with aneurysm, integrating information from the geometrical parameters obtained from periodic check-up, as alternative option to improve the accuracy of the rupture risk assessment with respect to the current indicator used by physicians. The first results of the validation tests have been satisfactory, as they have allowed detecting aneurysms with a high risk of rupture, but whose maximum diameter was less than the threshold value for repair.

For the initial validation tests, one clinical case and three cases from the literature with very different geometrical parameters have been selected.

In the first case, the state of a 74 years old male patient with an aneurysm is assessed. The geometric parameters of his aneurysm, obtained from a CT scan, and the GBFs and rupture index result, are shown in Fig. 2.

The geometrical characterization shows that the peak diameter is inferior to the threshold value (50 mm), therefore under current medical practice, the patient should be kept under observation. But, on the other hand, the values of the diameter rate and the asymmetry index fall into the high risk level interval. It must be noticed that by means of statistical analysis these geometric biomechanical factors are considered as the most influential factors on the aneurysm potential rupture.

Other two GBFs are sorted as high risk level, although their weight on the rupture phenomenon is lower. Finally, the value of the patient-specific quantitative predictor RI(t)=0.64 indicates that the elective repair should be considered.

Utilizing the 2D images set from CT, this aneurysm was reconstructed with the help of the software InVesalius (CenPRA, Campinas, Brazil) and it has been observed then that it is characterized by a high degree of artery deformation and asymmetry, as described in [8].

These results were confirmed because, during the period of check-up examination, the patient underwent an emergency surgical procedure for aneurysm rupture in the posterior wall.

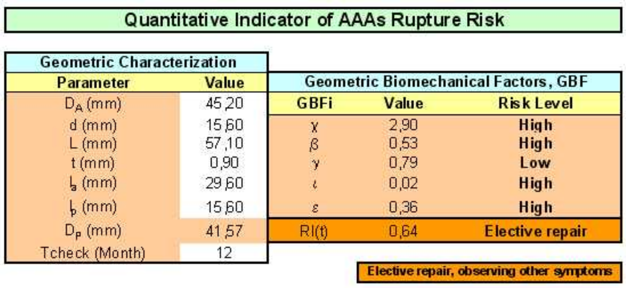

Fig. 2 Aneurysm rupture risk indicator: geometric parameters and recommendations for physicians[1]

In another test, a triple validation was performed comparing the results documented in the original papers [5], [9] and [10], the results presented by [2] and the results obtained here. All those results are summarized in Table II.

In essence, the validation analysis by the proposed method is in compliance with the results of [2].

[1] In the first check-up, DP is estimated from the expression used in [2]. In the following check-up, DP is the DA value of the previous check-up.
The values with the background in white are introduced by the user. The rest of the values are calculated through the method proposed in this document.

TABLE II
VALIDATION OF RUPTURE RISK INDICATOR

Parameters	Raghavan et al. model	Wang et al. model	Wilson et al. model
Maximun diameter, *D* (cm)	5.5	6.1	6.36
AAA length, *L* (cm)	10.8	8.4	10*
AAA wall thickness, *t* (cm)	0.19	0.18	0.2*
Growth rate, ε cm/year	0.43	0.54	0.61
Asymmetry, β	0.9	0.33	N/A
SP(t) Kleinstreuer & Zhonghua (2006)	0.5	0.6	0.75
Risk level Kleinstreuer & Zhonghua (2006)	Elective Repair	Elective Repair	Possible rupture
RI(t) present work	0.55	0.63	0.72
Risk level, present work	Elective Repair	Elective Repair	Possible rupture
Patient status (clinical)	Waiting for repair	Waiting for repair	Ruptured

The geometries of the different AAAs are very different, however the value of RI(t) is able to sort patients correctly. In the model presented in [5], it is noticed that the aneurysm affects a significant region of the aorta and has a high rate of growth, which has a high relative importance in the value of RI(t).

In the [9] model, the two biomechanical factors that have more influence in the deterioration of the aneurysm increase in comparison with the previous one, but they stay in the range of elective repair, although it was expected that the indicator value would be higher.

Analyzing the [10] model, it is noticed that there is a worsening of most of the geometric parameters, the most important are a high growth rate, a maximum diameter 20% greater than the threshold value and an aneurysm affecting a significant region of the artery. This behaviour justifies that the value of the rupture risk indicator falls into the category of possible rupture.

However, the results should not hide that, the complex and multifactorial phenomenon that characterize the formation, development and rupture of AAAs, establish a close relationship between individual parameters and biomechanical factors (biological and mechanical), and each one determines the behavior of the others. The proposed indicator will be useful, reliable and accurate, if it is able to identify high rupture risks in patients with aneurysm whose peak diameter is less than the threshold value, an aspect that is well documented in the literature [3], [1]

The most significant limitation of this method is associated with the accuracy in determination of geometric parameters. Especially the wall thickness, because of the difficulty of extracting an exact value (wide presence of surrounding tissues) and because of the variations between different regions of the aneurysm wall. Also the weighted coefficient and weighted level risk values, have to be reviewed and actualized with additional clinical statistics.

IV. CONCLUSION

The main conclusions drawn from present work are:

1) Through the study of the geometric parameters that characterize the AAAs, 5 GBFs have been defined conceptually and mathematically. It was determined by statistical analysis that Deformation rate (χ) and Growth rate (ε) are the most influential on the phenomenon of rupture.
2) The present method is based on a dimensionless parameter RI(t) which involves five geometric biomechanical factors associated with weighted coefficient and weighted level risk for AAA rupture risk assessment. Depending on RI(t) value, an initial block of recommendations is suggested to the physician about the AAAs patient treatments.
3) Four cases (not enough) were used to validate the potential clinical application of the obtained quantitative indicator and the results coincide with those reported in the literature.
4) The prediction of the rupture of small aneurysms is very complicated but very important. Regarding to the initial results; the method, as monitoring system of the development process of AAA, could be able to assess the risk of rupture in these pathologies.
5) From results presented here, a study with a control group and appropriate patient numbers has begun involving twelve aneurysm cases at the Clinical Hospital of Valladolid-Spain.

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