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On growth measurements of abdominal aortic aneurysms using maximally inscribed spheres

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ABSTRACT

The maximum diameter, total volume of the abdominal aorta, and its growth rate are usually regarded as key factors for making a decision on the therapeutic operation time for an abdominal aortic aneurysm (AAA) patient. There is, however, a debate on what is the best standard method to measure the diameter. Currently, two dominant methods for measuring the maximum diameter are used. One is measured on the planes perpendicular to the aneurism's central line (orthogonal diameter) and the other one is measured on the axial planes (axial diameter). In this paper, another method called 'inscribed-spherical diameter' is proposed to measure the diameter. The main idea is to find the diameter of the largest sphere that fits within the aorta. An algorithm is employed to establish a centerline for the AAA geometries obtained from a set of longitudinal scans obtained from South Korea. This centerline, besides being the base of the inscribed spherical method, is used for the determination of orthogonal and axial diameter. The growth rate parameters are calculated in different diameters and the total volume and the correlations between them are studied. Furthermore, an exponential growth pattern is sought for the maximum diameters over time to examine a nonlinear growth pattern of AAA expansion both globally and locally. The results present the similarities and discrepancies of these three methods. We report the shortcomings and the advantages of each method and its performance in the quantification of expansion rates. While the orthogonal diameter measurement has an ability of capturing a realistic diameter, it fluctuated. On the other hand, the inscribed sphere diameter method tends to underestimate the diameter measurement but the growth rate can be bounded in a narrow region for aiding prediction capability. Moreover, expansion rate parameters derived from this measurement exhibit good correlation with each other and with growth rate of volume.

In conclusion, although the orthogonal method remains the main method of measuring the diameter of an abdominal aorta, employing the idea of maximally inscribed spheres provides both a tool for generation of the centerline, and an additional parameter for quantification of aneurysmal growth rates.

1. Introduction

An abdominal aortic aneurysm (AAA) is the localized enlargement of the abdominal aorta that affects a large part of the elderly population; and the more it dilates, the more it will become prone to rupture that is associated with a high mortality rate. Current treatments involve surgical, and either open or endovascular repair. Unfortunately, the risk of these approaches is also high. Therefore, there is an imperative need to decide whether or not an AAA patient needs a medical intervention. Nonetheless, there is no solid argument regarding the appropriate time for an AAA patient to undergo surgery [1–3]. In clinical practice, aneurysms with diameters larger than 50 or 55 mm are considered for surgical intervention [4–10]. There are, however, uncertainties about the methods of measurement of the diameter [11–14], quantification of dynamic factors [2,15,16], and even sufficiency of the diameter as a predictor for AAA size evolution [1,3,15–19]. These uncertainties have led others to suggest other parameters: the AAA volume, blood pressure, age, sex, and calcium level as predictors for the time of surgery for AAA patients [1–3, 20–22].

Previous studies have utilized various ways of measuring the maximum diameter of an AAA and its growth rate. Although investigators have suggested different methods, most of them involve finding

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the maximum diameter either on an axial plane ("axial diameter") or on a plane orthogonal to aorta's centerline ("orthogonal diameter") [12,13,16,21,23,24]. Major concerns associated with measuring the diameter are, however, the accuracy of the estimation and reproducibility of the method [13]. Abada et al. [11] recommended using the maximum anterior posterior or maximum transverse diameter on axial slices. Dugas et al. [13] studied differences of the axial and orthogonal diameter measurements and suggested that the axial diameter measurements overestimate the diameter and that the orthogonal diameter method is more reproducible. Kontopodis et al. [12] illustrated that the median of the differences between the two methods are not high but there are cases where the wide range of differences in measurement possibly affect therapeutic decisions. Those studies proposed that the orthogonal diameter can better represent the AAA size than the axial diameters do, while finding that the perpendicular plane to vessel centerline can result in measurement uncertainty.

Volume has been introduced as an alternative factor to assess aneurysm development in an AAA patient [2,12,15,16,18,25,26]. Raghavan et al. [26] have reported that AAA volume and rupture risk are correlated more strongly than diameter and rupture risk. In their study, to calculate the total volume of an AAA, the aneurysm is axially sliced and the cross sectional area of each axial slice is multiplied by the vertical distance between the centroids of two consecutive slices. Kleinstreuer and Li [2] proposed a severity parameter that integrates alterations of different biomechanical factors (such as maximum diameter and expansion rate) over time by a single value. Recently, Martufi et al. [16] suggested that monitoring only the maximum diameter for surveillance programs may wrongly reflect the expansion related to wall weakening. In their paper, centerline based tools have been introduced to compare the suitability of localized and global parameters. They claimed that monitoring localized spots of fast diameter growth might greatly enhance the efficiency of AAA surveillance programs. Additionally, growth of AAAs is measured by means of an exponential growth model. However, computing growth is somewhat of a subjective issue among researchers.

There are simple ways, of course, to define growth rates in different AAA size measurements (cf. [15] and [16]). One approach is quantifying the growth rate by calculating the change in the diameter divided by the time interval between two consecutive images in a linear fashion. Nonetheless, there are multiple practical issues associated with this method such as an inaccuracy due to a relatively small change in diameter over time, the nonlinear nature of the expansion [27], and so forth. Several studies have utilized an exponential growth function for predicting AAA expansion over time [15,16,21,28–30]. Although Martufi's study [16] suggested that an exponential growth parameter can capture AAA's growth, more studies need to be conducted to increase our understanding of an AAA growth pattern; hence, one of the objectives of this study is to examine whether the exponential growth pattern is reasonable so that it can provide a prediction capability for AAA clinical management.

The present study also introduces a new method for the AAA's diameter measurement. This method involves finding the diameters of maximally-inscribed spheres within the geometry, and consequently constructing the centerline using the series of spheres' centers. This idea has been widely used for different purposes among researchers [31–33]. We suggest that the proposed definition of the diameter carries useful information related to the size of the AAA, which can be used along with other methods to find the correlations among different geometric parameters and their growth rates. Additionally, this method possibly assists in prediction of the future progression of the disease.

To this end, an efficient computational algorithm is developed to compute the inscribed-spherical diameter, and the advantages of using this method are presented. Besides, an exponential growth pattern for maximum diameter is evaluated in the patient group.

2. Methods

2.1. Exponential growth rate

An exponential growth model is a widely accepted growth rate for many biological and physical occurrences. The growth model is proposed based on a nonlinear growth rate g introduced in [16].

$$g = (\mathrm{Exp}\,(12r) - 1) \times 100\ [\%/\mathrm{year}] \tag{1}$$

where the variable r is measured using a logarithmic growth rate

$$r = \frac{1}{t}\ln\left(\frac{X^{\mathrm{follow-up}}}{X^{\mathrm{baseline}}}\right). \tag{2}$$

The quantity X is measured and t is the time interval between two consecutive images in months. To calculate the logarithmic growth rate, the two quantities, $X^{\mathrm{follow-up}}$ and X^{baseline}, are at the same position on the normalized centerline.

Eq. (1) combined with Eq. (2) can be rewritten for the maximum diameter D as below

$$D^{\mathrm{follow-up}} = D^{\mathrm{baseline}}\left(1 + \frac{g}{100}\right)^{\frac{t}{12}}. \tag{3}$$

It is equivalent to the following form:

$$D^{\mathrm{follow-up}} = D^{\mathrm{baseline}} e^{kt} \tag{4}$$

where

$$k = \ln\left(1 + \frac{g}{100}\right)\Big/12. \tag{5}$$

Using these equations, an exponential function can provide a curve representing the evolution of the maximal diameter versus time for all the patients. Since the first scan time on monitoring the disease progression of the patients is not the same, each set of data is unfixed with respect to time, without changing the time intervals between two successive images. However, the values measured for diameters are maintained the same. An initial curve is then chosen and the patient's data are moved to match the exponential curve using the least square method. Then another curve is fitted and the process continues iteratively until a certain minimum amount of error is reached. This general exponential curve can be employed to achieve a better understanding of an AAA size and a more accurate prediction of the evolution of the disease.

2.2. CT scan data

This study was subject to Internal Review Board approvals at Michigan State University and Seoul National University Hospital.

A total of 59 computed tomography (CT) scan data for 14 AAA patients were obtained from Seoul National University Hospital, South Korea. Patients were scanned repeatedly between 3 and 56 months, and the median was 8 months for all of the follow-up periods. The scans were performed using a 100 kV, 88 mA s Somatom Sensation 16 CT scanner (Siemens Healthcare, Erlangen, Germany). The slice thickness is 1 mm and 2D pixel size is 0.641 mm. Further information about the patients is presented in Table 1.

2.3. Maximally inscribed sphere diameters

A biomedical software, MIMICS® (Materialize, Leuven, Belgium), is used to reconstruct segmented 3D longitudinal CT data. A smoothing operation is performed after segmentation to sooth down the roughness of the surface resulted from automatic segmentation.

Three-dimensional point clouds for the AAA wall with iliac arteries are acquired from the software as an embodiment of the volume of the abdominal aorta (Fig. 1). The point cloud model is essentially a subset of a stereo-lithography (STL) model constructed solely of the vertices of the STL model, which is comprised of four surfaces: two

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