Original

Received
July 20, 2005

Revision accepted
Nov. 14, 2005

Code No. 251

Computational Flow Dynamics in Abdominal Aortic Aneurysm Using Multislice Computed Tomography

SHUJI YAMAMOTO, SHIGERU MARUYAMA,¹⁾
YUSUKE NAKAHARA,²⁾ SHIGERU YONEYAMA,³⁾
SHINICHIRO TANIFUJI,²⁾ SHIGEO WADA, SEIKI HAMADA,⁴⁾
MITSURU KOMIZU,⁴⁾ TAKESHI JOHKO,⁵⁾
MASAO DOI,⁶⁾ and TAKAMI YAMAGUCHI

Department of Bioengineering and Robotics, Graduate School of Engineering,
Tohoku University

1)GEO Planning Co., Ltd.

2)Plamedia Co., Ltd.

3)Maxnet Co., Ltd.

4)Department of Radiology, Osaka University Graduate School of Medicine

5)Department of Medical Physics, Osaka University Graduate School of Medicine

6)Department of Applied Physics, The University of Tokyo

Introduction

In the rapidly evolving field of abdominal aortic aneurysm (AAA) therapy, preoperative imaging is becoming increasingly important.^{1,2)}

Rupture of AAA is one of the most urgent vascular conditions and requires rapid intervention.³⁾

Diagnostic devices for AAA have included intraarterial digital subtraction angiography (DSA) and CT angiography (CTA). Recently, CTA has emerged as a minimally invasive alternative to intraarterial DSA for assessing the abdominal, thoracic, and cranial vasculature.^{4,5)} multislice computed tomography (MSCT) scanning is a critically important hardware development in terms of speed of acquisition, but, for it to be used in clinical practice, software to enable better three-dimensional (3D) imaging must be made available. It is through the rapid development and achievements of technology

that such needs are met in the areas of graphics computing, virtual interaction, and tactile feedback systems, creating a synergy of research that enhances visualization in medicine. However, most 3D visualization in medicine has paved the way to the development of systems that focus on creating realism through visualization. Such virtual realism could be exhibited in visualizing the structures or in visualizing the functions through simulation and modeling. Aneurysm rupture is a biomechanical phenomenon that occurs when the mechanical stress acting on the inner wall exceeds the failure strength of the diseased aortic tissue. In such cases, a simulation approach for AAA would be useful to evaluate the effects in pre- and postoperative cases using computational flow dynamics (CFD). Our goal was to create seamless integration from clinical data acquisition to conversion for 3D-CFD in a patient-specific model of AAA.

Summary

Following the introduction of a new multislice computed tomography (MSCT) scanner, it has become possible to produce high-speed CT angiography (CTA), the preferred method for imaging in emergent abdominal vascular conditions. Unlike catheter angiography, multislice CTA not only depicts the vessels but also allows perfusion in adjacent organs to be assessed. To make the most effective diagnostic use of multi-detector row CTA and three-dimensional image post-processing, radiologists must be familiar with the optimal CTA protocols and the typical CT findings in various emergent vascular conditions using computational flow dynamics (CFD). This article describes a technical approach to estimating the blood flow state of human abdominal aortic aneurysm (AAA) in more detail by constructing realistic three-dimensional (3D) vessel models using CFD methods, focusing on pre- and postoperative cases.

Key words: AAA, CFD, MSCT

別刷資料請求先: 〒164-0003 東京都中野区東中野1-45-10 カーサフォレストーネ301号
山本修司 宛

1. Methods

1-1 Image acquisition

A clinical data set for AAA was collected in a 76-year-old male patient who underwent scanning as part of normal clinical practice with standard CTA protocols. Written informed consent was obtained for the release of CT data in accordance with the guidelines of the Osaka University Hospital review board. The patient underwent CTA for follow-up during the 3 years from May 1999 to October 2002. Straight graft replacement was performed for the lesion in this case.

The scan parameters for AAA studies were fixed at 120 kVp and 0.5-sec rotation speed using 4-slice MSCT (Aquilion VZ, Toshiba Co., Tokyo, Japan). First, a pre-contrast helical scan of the whole abdominal area was performed at a low dose of less than 100 mAs as screening. Then, a contrast enhanced study was carried out using biphasic helical CT scanning. Enhancement was achieved with 100 ml of non-ionic iodinated monomer solution with a concentration of 300 mg/ml injected at a flow rate of 2.0 ml/sec. In the first phase of enhancement, scan delay was determined as the interval from the start of injection using an automatic bolus-tracking system. The optimal transit time from intravenous injection to enhancement of the abdominal aorta was determined using a region of interest (ROI) placed on the aorta at the slice level of the superior border of the aortic arch. Scanning was started at the time determined by a contrast bolus-tracking technique to coincide with peak aortic enhancement of 150 HU. After the automatic bolus-tracking scan, helical scanning (at 120 kV and 200 mA) of the whole abdominal area was performed, with a 0.5-sec rotation time and helical pitch of 6:1. Finally, 90 sec after scanning of the first phase, re-scanning of the same area was carried out for a complete check of the intravenous phase.

1-2 Three-dimensional modeling of abdominal aortic aneurysm

Slices acquired in the early phase of the contrast study were reconstructed retrospectively at a 2 mm slice thickness at 1 mm intervals for 3D visualization and analysis. The slices were transferred to personal computers using the DICOM query and retrieve function. The boundary of the inner AAA wall was identified using grayscale thresholding and semi-automated edge detection. Thresholding was applied using the technique based on features of the image histogram containing the en-

hanced lesion. A simple shape-based method applied to the bi-modal histogram (contrasted and non-contrast enhanced parts) selects the threshold as the minimum value between the two histogram peaks. The Marching Cubes algorithm was applied to generate the AAA surfaces, and an advancing front method was applied to fill each region defined by the surface data with tetrahedral patches using AmiraDev (Mercury Computer Systems, Inc., Chelmsford, MA, USA). In this case, both the topology and geometry are completely unstructured. The cell type of this surface of the model can be combined in arbitrary combinations in an unstructured grid. Unstructured grids are found in fields such as finite element analysis. The models were generated for pre- and postoperative AAA cases, with tetrahedral elements comprising 177,719 and 189,918 nodes, respectively. Additionally, we developed arbitrarily cutting plane modules for the accurate input and output of blood flow and pressure. This can reduce computational error in setting the orthogonal inlet and outlet along the vascular line. This module is a contributed class that offers high-performance image resampling along an arbitrarily oriented volume.⁶⁾ It can also extract oblique slices from the volumes. A schematic diagram of these techniques is shown in Fig. 1.

1-3 Governing equations and boundary conditions

Incompressible, homogeneous, Newtonian flow is simulated for stationary and transient fluid using CFD solver (AcuSolve, ACUSIM Software Inc. and SUNDYTETRA, Plamedia Co, Ltd.) The x, y, z, and t momentum and continuity equations are given in compact form by Eq. 1a and 1b, as follows:

$$\rho \left[\frac{\partial V}{\partial t} + (V \cdot \nabla) V \right] = \eta \nabla^2 V - \nabla P \quad \text{..... (1a)}$$

$$\nabla \cdot V = 0 \quad \text{..... (1b)}$$

Where, V is the velocity vector. Incompressible flows satisfy the divergence-free condition for velocity ($\nabla \cdot V$). ρ , η and P are blood density, viscosity, and pressure, respectively. Details of the calculation of this incompressible Navier-Stokes equation were solved using the implicit method, as follows:

$$\rho \frac{V_{n+1} - V_n}{\Delta t} = -\rho (V_{n+1} \cdot \nabla) V_{n+1} + \eta \nabla^2 V_{n+1} - \nabla P_{n+1} \quad \text{..... (2a)}$$

$$\nabla \cdot V_{n+1} = 0 \quad \text{..... (2b)}$$

Where, the number of $n+1$ is the final output used to solve the equation. Finally, blood flow is simulated for the following parameters by blood properties: blood density $\rho=1.06 \text{ g/cm}^3$, blood viscosity $\eta=0.0471 \text{ poise}$, inlet velocity $U=50.0 \text{ cm/sec}$ (stationary case)and inlet diameter $L=2.5 \text{ cm}$. The Reynolds number(Re)was calculated as follows:

$$Re = \frac{\rho UL}{\eta} \approx 2800 \dots\dots\dots (3)$$

The same parameters were input into the pre- and postoperative AAA cases.

The calculated x , y , and z components of blood velocity and pressure were visualized in a 3D vector field using illuminated field lines.⁷⁾ The module computes a large number of field lines by integrating the vector field starting from random seed points of AAA. The lines are displayed using a special illumination technique that gives a much better spatial understanding of the field's structure than ordinary constant-colored lines. The streamline parameters(number of lines, length, opacity, and fade) for visualizing the velocity map and pressure values were set at same condition for pre- and postoperative AAA cases. Arbitrary 3D vector fields were converted to axial cutting planes(6 slices for pre- and postoperative AAA cases)on the level of the lesion with a line integral convolution(LIC)algorithm.⁸⁾ The LIC algorithm works by convolving a random noise image along the projected field lines of the incoming vector field using a piecewise linear hat filter. The synthesized texture clearly reveals the directional structure of the vector field inside the cutting plane. RGB color map of the LIC is derived to convert the vector to a scalar field increasing with blood velocity from blue(low magnitude)to red (high magnitude) Quantitative evaluation between pre- and postoperative AAA cases was performed to calculate the percentages of the area representing high blood velocity(colorized red area)to the area of intravascular lumen in the slices with colorized LIC.

2 . Results and Discussion

The automatic bolus-tracking technique was an effective method to estimate with peak aortic enhancement of the entire abdominal area. This method provides constant quality of target anatomical objects with surface rendering. Figure 2 shows an example of the extraction of a contrast enhanced area of AAA. Segmentation based on a shape-based method for the bi-modal histogram ac-

Fig. 1 Schematic diagram of the technique used in blood flow visualization and analysis. Diagram shows the procedure from the acquisition of DICOM CT data to CFD display via image processing and analysis.

curately selected the contrast enhanced area in Fig. 2a. AAA surfaces produced a detailed inner wall of AAA by the Marching Cubes algorithm(Fig. 2b, c) Figure 3 shows the results of surface rendering in both pre- and postoperative cases. Both rendered images presented equivalent quality of the AAA model by automatic bolus-tracking. Figure 4 shows an example of cutting the inlet for optimal setting of the blood flow parameter. This cutting module can slice through the dataset(AAA model) with a plane to create a planar cut. The cutting surface interpolates the data as it cuts, which then can be visualized using any standard visualization technique. This module supported the translation from a 3D visualization process to the CFD solver. In this study, we used a commercially available CFD solver. Many foundations have evaluated mathematical accuracy with convergence proofs, error estimation, and localization proofs using the CFD solver. In this study, we used the standard parameter of blood flow characteristics of the adult human model based on the previous work of computational biomechanics in a cardiovascular system.^{9,10)}

Finally, numerical integration was performed with vector visualization algorithms(illuminated field lines and LIC) The resulting streamlines of blood flow and pressure are shown in Fig. 5. The lesion of streamline in the preoperative AAA case contained turbulent eddy flow, unlike the postoperative AAA case in Fig. 5. This

Fig. 2 Marching Cubes algorithm with segmentation.

(a) Segmentation of abdominal aorta, (b) 3D surface display, and (c) Tetrahedral patches.

a | b | c

Fig. 3 Pre- and postoperative CT study using the automatic bolus-tracking technique.

(a) Preoperative 3D image and (b) postoperative 3D image.

a | b

indicates improvement of congestion in the postoperative case. The same results can be evidenced in more detail in the color display of the state of turbulence of eddy flow in the LIC display (Fig. 6). As a result of quantitative analysis by colorized LIC, the postoperative case had improved blood velocity compared with the preoperative case in this simulation study. Percentages of the area representing high blood velocity (colorized red area)

to the area of intravascular lumen were higher in the postoperative than in the preoperative case. Furthermore, from the numerical results, it appears that a significant difference was observed in the level of maximum diameter of the lesion preoperatively (ratios of the red area in LIC were 41.9, 17.7, 11.8, 11.5, 14.1 and 18.0% preoperatively and 57.0, 40.6, 30.7, 24.7, 24.8, and 22.8% postoperatively for slices on the lesion) Figure 7 shows

Fig. 4 Example of selecting the arbitrary cutting plane for optimal input and output parameter settings of blood flow.

Fig. 5 Visualization of blood pressure and velocity for pre- and postoperative AAA. (a) Color map of blood pressure and (b) flow velocity map using illuminated field lines for display.

Fig. 6 Line integral convolution(LIC)display of the lesion in pre- (a) and postoperative AAA (b). Percentages of the area representing high blood velocity(red area)to the area of intravascular lumen are shown under the slices, respectively.

Fig. 7 Percentage of the area representing high blood velocity on the 6-slice level of a lesion using the LIC algorithm(pre- vs. postoperative AAA)

this result. Thus, the blood flow state of the AAA cases was quantitatively improved by the surgical operation. However, this simulation must be verified by experimentally obtained facts. Moreover, a more detailed, practical, technical approach is needed, one that considers the relationship between residence times, activated fluid, and fluid viscosity, instead of the less complex linear form used in the AAA cases. Although the results of this study supplement a rather limited empirical knowledge base about blood flow parameters, blood density ρ , blood viscosity η , inlet velocity U , and inlet diameter L , more research regarding the acquisition of patient-specific blood-flow parameters is required. Functional MSCT to measure blood flow parameters is a subject for future study. Until recently, various conditions have been less than satisfactory, and CFD-applied medical imaging was not widely used because of the problems of poor time and spatial resolution in medical examination devices.

Currently, new methods are being developed for use with high-performance magnetic resonance imaging(MRI) and ultrasonic Doppler methods.^{11,12)} It is hoped that cooperation among the related fields will become closer.

3 . Conclusion

Computational flow dynamics were effective for estimating the blood flow state of the cardiovascular system in specific cases. The computer simulation with medical 3D modeling used in this study was shown to be very valuable for surgical planning and estimation of surgical operations in cases of AAA.

Acknowledgment

This work was supported by the Tohoku University 21 COE Program “Future Medical Engineering Based on Bio-nanotechnology.”

References

- 1) May J, White G, Waugh R, et al.: Treatment of complex abdominal aortic aneurysms by a combination of endoluminal and extraluminal aortofemoral grafts. *J Vasc Surg*, 19(5) 924-933(1994)
- 2) Verbin C, Scoccianti M, Kopchok G, et al.: Comparison of the utility of CT scans and intravascular ultrasound in endovascular aortic grafting. *Ann Vasc Surg*, 9(5) 434-440, (1995)
- 3) Alcorn HG, Wolfson SK Jr, Sutton-Tyrrell K, et al.: Risk factors for abdominal aortic aneurysms in older adults enrolled in the Cardiovascular Health Study. *Arterioscler Thromb Vasc Biol*, 16(8) 963-970(1996)
- 4) Dillon EH, van Leeuwen MS, Fernandez MA, et al.: CT angiography: application to the evaluation of carotid artery stenosis. *Radiology*, 189(1) 211-219(1993)
- 5) Rubin GD, Dake MD, Napel S, et al.: Three-dimensional CT angiography as an alternative to conventional arteriography in planning and in vivo evaluation of aortic stent grafts(abstr) *Radiology*, 189, 112(1993)
- 6) The VTK User's Guide, Version 4.2, pp.114-115, Kitware Inc.(2003)
- 7) Zöckler M, Stalling D, and Hege HC: Interactive visualization of 3D-vector fields using illuminated streamlines, *Proc. IEEE Visualization '96*, pp.107-113(1996)
- 8) Stalling D, and Hege HC: Fast and resolution independent line integration convolution. *Computer graphics proceedings. Annual Conference Series*, pp.249-256(1995)
- 9) Yamaguchi T: Computational visualization of blood flow in the cardiovascular system, in *biological flows*, M.Jaffrin and C.C. Carø(Eds) Plenum Press, New York, pp.115-136(1995)
- 10) Yamaguchi T: Computational visualization of blood flow, in *computational biomechanics*, Springer-Verlag, Tokyo, pp.165-184(1996)
- 11) Saber NR, Wood NB, Gosman AD, et al.: Progress towards patient-specific computational flow modeling of the left heart via combination of magnetic resonance imaging with computational fluid dynamics. *Ann Biomed Eng*, 31(1) 42-52(2003)
- 12) Nakamura M, Wada S, Mikami T, et al.: Computational study on the evolution of an intraventricular vortical flow during early diastole for the interpretation of color M-mode Doppler echocardiograms. *Biomech Model Mechanobiol*, 2(2) 59-72(2003)

図表の説明

- Fig. 1 血流の可視化と解析の手順概略図
ダイアグラムは、画像処理と解析を通して、DICOMデータからCFD表示までの手順を示すものである。
- Fig. 2 マーチンキューブ法を用いた血管の領域抽出
(a)腹部血管の領域抽出, (b)三次元サーフェス再構成, (c)4 面体パッチ法による表面拡大図
- Fig. 3 自動ボーラストラッキング機構による手術前後のCT施行例
(a)手術前三次元画像, (b)手術後三次元画像
- Fig. 4 適切な血流の入出力条件を設定するために任意切断面を決めているシーン
- Fig. 5 術前および術後のAAA症例の血圧と血流速の可視化の結果
(a)血圧のカラーマップ表示, (b)illuminated field lines法による血流速の表示
- Fig. 6 術前、術後の動脈瘤部におけるline integral convolution(LIC)表示例
(a)術前のAAA症例, (b)術後のAAA症例
パーセント表示は、血管内面積における血流速度が速い部分の面積率を示す。
- Fig. 7 血管内面積における血流速度が速い部分の面積率のグラフ表示(術前と術後AAA症例との比較)