INTRODUCTION

The number of publications regarding computational fluid dynamics (CFD) for intracranial (IC) aneurysms has grown rapidly in recent years (1). In addition, non-invasive MR angiography reported a higher prevalence of unruptured aneurysms in a population without comorbid conditions (2). This result might influence the disease conceptualized as rare and fatal to not-rare and more preventable one before rupture. Some physicians hope to distinguish flow changes after flow diverter treatment. Changes in flow dynamics within the aneurysm might be helpful to anticipate the obliteration of aneurysms (3). The current trend and clinical environment resulted in the release of a software (SW) by the vendor, Siemens CFD SW (prototype, not commercial available; Siemens AG, Erlangen, Germany).

Although sophisticated results of CFD have been presented in many publications, reviewers criticize that most researches did not consider numerous variables, as follows (1): thickness of vessel wall, elasticity of vessel wall, flow velocities at inlet and outlet, and adequacy of the model. However, we consider that CFD is just a simulation with accepted assumptions because of difficulties to obtain model specific wall thickness, flow conditions at all openings, etc. CFD produces many numerical values and graphic visualizations, similar to reality. Nevertheless, the
impact of three dimensional (3D) modeling for CFD analysis has not been published to date. Researches for proper modeling of carotid bifurcation have been presented by some publications. Moyle et al. (4) suggest that given a sufficient entrance length of realistic geometry, simplification to fully developed the axial flow (i.e., Womersley) may be made without penalty. In the report of Hoi et al. (5), CFD models of the carotid bifurcation incorporate at least three diameters of the common carotid artery length, if fully developed velocity profiles are to be imposed at the inlet. Only recently, a study for the entrance length of an IC aneurysm was conducted for ophthalmic artery (OA) aneurysm (6).

In practicality when using conventional angiography as a source of 3D vessel model, many difficulties arise to obtain full entrance length from cervical internal carotid artery (ICA). Beam hardening artifact form skull base could be due to the poor 3D imaging quality to petrous segment of ICA. In conditions of short neck stature or distally located catheter tip, the imaging of cervical and petrous segment of ICA is prevented.

Thus, this study assumed that shorter entrance length from the parent vessel of aneurysm might show a different flow to that of longer entrance. The aim of this study is to evaluate the influence of entrance length, and to compare the two different solutions for CFD analysis with distal ICA aneurysm. Two models with different entrance length were assessed by using two different CFD solvers, prototype and commercial tools (commercials). The entrance length was preserved as long as possible, without having any artifacts. After cropping the models, the 3D surface mesh generation was continued (Fig. 1). One inlet at the proximal end of entrance, and more than two outlets at the distal end of flow exit, were determined by adding cutting planes. Completed files were saved in the Stereolithography (STL) format as the original model. The IC model was made from the original model by removing cervical and petrous segment of ICA, by adding cutting the plane as an inlet at ascending cavernous segment of ICA. Minimal length of distal end at outlet was removed from original model when adding cutting planes as outlets. The prototype did not have identifiable or independent steps to make 3D volume meshes, such as 3D tetrahedral mesh which is essential in commercial SW.

MATERIALS AND METHODS

Between January 2012 to June 2014, 12 vascular models from 11 patients with distal ICA aneurysm were enrolled in this study. Data acquisition and reconstruction of 3D geometry imported from the 3D angiography, was obtained using an AXIOM Artis Zee (Siemens AG, Erlangen, Germany) digital biplane angiography. The patient identification was deleted from the data analysis. This study was approved by our Institutional Review Board, after submission of exemption form for informed consent. All 12 3D models had enough cervical ICA length, which was more than five times (5) their diameter.

IC models were made by removal of the cervical and petrous segments of ICA from original ones. Thus, IC models only had the cavernous segment of ICA and carotid siphon, prior to distal ICA which had the aneurysm. The CFD results of two different solvers were also compared. The prototype used was a single package SW composed of segmentation, mesh generation, analysis and visualization steps. The commercial SW was composed of independent SWs for each step.

Step 1: Segmentation and Mesh Generation

 Prototype
 Axial source files from Synco (Siemens AG, Erlangen, Germany) workstation were obtained using large field of view (FOV) reconstruction. These were loaded to the prototype in different workstations, to make 3D geometry. Removal of small vessels is essential for saving time and unnecessary effort, since exclusion of small diameter vessels usually does not affect the CFD results (7). Small branches were removed using the cropping tool. These were distal vessels from distal M1 segment of the middle cerebral artery (MCA), distal A1 segment of the anterior cerebral artery (ACA), and tiny branches of distal ICA. Segmented outlets of models were MCA, ACA, OA and posterior commu- nication artery (Pcom). Occasionally, OA and Pcom were separated when their diameter was smaller. The entrance length was preserved as long as possible, without having any artifacts. After cropping the models, the 3D surface mesh generation was continued (Fig. 1). One inlet at the proximal end of entrance, and more than two outlets at the distal end of flow exit, were determined by adding cutting planes. Completed files were saved in the Stereolithography (STL) format as the original model. The IC model was made from the original model by removing cervical and petrous segment of ICA, by adding cutting the plane as an inlet at ascending cavernous segment of ICA. Minimal length of distal end at outlet was removed from original model when adding cutting planes as outlets. The prototype did not have identifiable or independent steps to make 3D volume meshes, such as 3D tetrahedral mesh which is essential in commercial SW.

 Commercials
 The 3D files made from the prototype were further edited for commercials. These files only had surface triangular meshes,
and were essential to make 3D volume meshes composed of tetrahedrons for subsequent simulations. Most of the triangles were of even shape and size, but few were in-equilateral triangles (Fig. 1), had free edges and were duplicated. These were mostly located within 1 cm from the inlet and outlets, and were responsible for the errors of generation of 3D tetrahedral volume meshes. For the valid subsequent 3D volume mesh generation, these unacceptable triangles were removed and re-meshed manually using Hypermesh (Altair Engineering, Inc., Troy, MI, USA). After the re-meshing, the non-circular shape of the inlet and outlets were modified into circular ones, as similar to the natural contour and area as possible. Final 3D surface mesh file were saved into the original model, which were used as the template for making the IC model. After the 3D tetrahedral mesh generation, volume mesh files were saved as Nastran file for next step, namely simulation.

Fig. 1. Case 2. Segmentation and mesh generation. Prototype (A–D) and commercials (E, F).
A. Virtual rendering shows small vessels.
B. Model generation with surface triangular mesh after removing small vessels.
C. Original model: model processing by adding cutting planes (arrows) and defining them as inlet or outlets. Note the in-equilateral triangles (yellow box) at inlet.
D. Making IC model from original model. New inlet of IC model is made by adding cutting plane at the ascending cavernous segment of internal carotid artery.
E. Imported model from prototype shows non-circular shape of outlet and in-equilateral triangles (arrowhead).
F. After re-meshing, model has circular outlet (yellow, arrowheads) and even shaped triangles.
IC = intracranial
IC models were made from original models edited by commercials. Referring to the IC model of prototype, we removed some length of the entrance vessels, including cervical and petrous ICA. Outlets were applied same as in original models, contrasting the prototype. The processes which followed after making the circular inlet were the same as with the original models.

Step 2: Simulation

Identical parameters were used for simulating both the prototype and commercials, keeping following material constants: the blood density $1000 \text{ kg/m}^3$, and blood dynamic viscosity $0.004 \text{ Poiseuille}$. The number of 3D tetrahedral volume mesh was approximately 50000 to 200000. The flow velocity at inlet used the inflow curve provided by the prototype. The boundary conditions at the inflow boundary were used on the pulsatile periodic flow rate, with peak systolic velocity of 300 and end diastolic velocity of 127 mm/sec. The unsteady flows in the ICA were computed over an interval of two cardiac cycles. Simulation intervals were about 0.05 seconds. Finally, we assumed the 2nd cardiac cycle data as results.

Prototype

After segmentation, the 3D surface mesh generation into STL file formation and simulation process was continued directly. There was no independent step of volume mesh generation, as performed for commercials. The manual of the prototype instructed to press the "start simulation" for "to start the meshing and the simulation". It declared that it operates on the scheme of Navier-Stokes solver.

Commercials

The commercial SW used was the finite element and volume SW ADINA ver. 8.9 (ADINA R & D, Inc., Watertown, MA, USA). Blood flow was assumed to be laminar, viscous, Newtonian and incompressible. No-slip boundary conditions were assumed for the flow viscosity produced between the fluid and the wall surface of the blood vessels. Only the atmospheric conditions were applied for outlets.

Step 3: Visualization

Prototype

After the simulations, activation of the “visualize simulation result” loaded the results. Various outputs were observed, including the classical ones such as wall shear stress, velocity, and wall pressure, and also graphic enforced ones as like streamline, pathline, streakline and particles which are the dedicated visualization of flow vectors.

We made the cutting planes of velocity profiles at inlet and outlets within 1 cm of their ends. These planes were perpendicular to centerline of the vessel. Cutting planes of parent vessels were also made, including sac and neck of aneurysm. We referred to images made from commercials, since they were easier to make using the centerline and sharing the common global coordinates between original and IC models. The maximum value of velocity scale (MV) was considered as maximum flow velocity during peak systole of cardiac cycle. Velocity scale was automatically generated from peak to zero (Fig. 2).

Animations of pathline were made with the working projection, which revealed the profile view of aneurysm neck. A pathline is defined as the trajectory that an individual particle will follow, once it is placed in the fluid domain. It is provided as a movie with more intuitive picture and fluid motion (Fig. 3).

Commercials

EnSight Gold v10.x (CEI, Inc., Apex, NC, USA) was used for visualization of CFD results. This allowed processing the original and IC model simultaneously (Fig. 2). Cutting planes were identically obtained at the outlets and parent vessel, in both the original and IC models, since they both have common global coordinates. However, the cutting planes of inlet were individually made, as both have their resective global coordinates. The MV was considered as the maximum flow velocity during peak systole. Velocity scale was automatically generated from peak to zero.

Pathlines were also obtained on both models at the working projection.

With both solutions, we captured the last frame of pathlines. The visualized pathlines within the sac of aneurysm were graded as: 0, no pathlines within sac; 1, filling less than one third nearby neck; 2, filling one third to two third; and 3, filling more
than two third of the sac.

Statistical Analysis

Wilcoxon signed rank test was used for the comparison of MV. Correlations of MV between solutions and models were re-
viewed by paired sample correlations of $t$-test. Marginal homo-
geneity test was used for comparing the pathline filling. Statisti-
cal significances were analyzed between solutions and models.

RESULTS

The prototype showed faster flow velocities presented as MV, as compared to commercials in both the models (original mod-
el, $p = 0.004$; IC model, $p = 0.002$) (Table 1). One exception was original model of case 9, having the largest aneurysm, showed faster flow with commercials. With IC models, MV of proto-
type and commercials showed high correlations (correlation = 0.828). But with original models, both solutions showed no correlation between the solvers (correlation = 0.667). Poor correlation was noted between two models using both solutions. In all cases, flow velocities at outlets were faster than at inlet. MCA was a representative vessel as outlet, because most flow exits were through it. Results of models having large aneurysm did not show consistent findings of MV. With models of small an-
eurysms less than 8 mm, original models had a tendency of faster flow than IC model on commercials ($p = 0.018$). Howev-
er, there was no statistical significance on prototype ($p = 0.063$). In case of large aneurysms, the IC models showed faster flow in prototype (case 9, 10, 11, and 12) and commercials (case 10, 11, and 12), but did not have statistical significance due to small sample size.

Captured image at the end of pathline animation shows the accumulation flow within the vessel and aneurysm sac (Fig. 3). Slow flow near the aneurysm wall is visible in the last part of the animation. Prototype could visualize more pathline fillings within the sac of aneurysm than commercial, in both the mod-
els (original model, $p = 0.05$; IC model, $p = 0.002$). Prototype showed pathline fillings more than commercials about one ($n = 11$) or two degree ($n = 8$). Only 4 models visualized similar pathline filling. The single model with poor pathline filling on
prototype was the one which showed pathline leak, as described below. Commercials could easily illustrate the overlapped vessel contour over pathline. On commercials, the vessel image of 3D surface contour was available which the product after the segmentation. However, with the prototype, the overlapped vessel images were complex in the original model which had unwanted vessels before the segmentation. These unwanted images disturbed the clear pathline visualization. Furthermore, with IC model, vessel images were not available on the prototype, which made it difficult to identify the contours of vessel and aneurysm.

Pathline leak from ICA to aneurysm sac is noted in case 7, using the prototype (Fig. 4). Pathline leak was more prominent at original than IC model. Flow continuity of leak was also noted in velocity cut plane (not shown). This artifact might be the
result of a kissing artifact during virtual rendering. Like other models, kissing artifact between adjacent vessels was frequently seen during segmentation. After the segmentation and mesh generation, intermediate products of 3D surface mesh did not show the kissing artifact. Furthermore, the original model of this case was the only example of poorer pathline fillings on prototype, as compared to the commercials. In contrast, commercials did not show a pathline leak, even though they used the same 3D surface mesh model produced by the prototype.

Analysis time of prototype was 4–5 times more than that of commercials. This might be the result of restriction of central performance unit (CPU) performance, which was less than 20–30% on the task management window. However, the CPU occupancy was nearly 100% during analysis as well as visualization steps in commercials. It took 15–40 minutes for ADINA simulation. Visualization also took effort and time for learning how to operate.

### DISCUSSION

Except one model of the large aneurysms (case 9), the MV by prototype were faster, almost double. Faster flow might be influence more pathline visualization in the prototype. Well visualized pathlines within the aneurysm sac on prototype might be more helpful for flow analysis. Considering that contrast material is usually filled within a second into the sac of an aneurysm on conventional angiography, the prototype might be more intuitive for visualization of flow into aneurysm sac. Overlapped vessel image on pathlines is essential for identifying vessel boundary. Prototype looks like drawbacks for viewing vessel simultaneously with pathlines.

Previous studies on the significance of the length of entrance vessel were focused on results at the aneurysm itself (6), but our study was focused on the outlet. We think it is an important determinate factor affecting the CFD results of an aneurysm. Using the IC model, correlation between the two solvers with original model is statistically disturbed because MV of IC models being faster than original with prototype, in case 9. Case 9 had the largest aneurysm of 20 mm, and it would be necessary for reviewing variable engineering considerations.

Although same boundary conditions and input velocity profiles were used by both solutions, minor differences existed in the 3D models analyzed by both solutions. Two distinct differences are the presence of in-equilateral triangular surface mesh, and a non-circular inlet/outlet in the prototype model. It could be postulated that these differences could affect the results. In addition, prototype does not have an independent step of 3D volume mesh generation. Only after making 3D surface mesh, the CFD simulations are directly activated. The manual of prototype only directs to "start simulation" for "to start the mesh generation and the simulation". It would be essential to declare more details for algorithm of prototype by the vendor.

Statistical significance regarding the length of entrance vessel did not show the might be diluted by the results of models with large aneurysm. There is the tendency of faster MV of the original model on both solutions, except models of large aneurysm.

### Table 1. Comparison of Flow Velocities and Pathline Visualizations between Two Models and Solvers

| Model | Size | P-MV | P-PF | P-PL | C-MV | C-PF |
|-------|------|------|------|------|------|------|
| 1     | 5 × 3 | Org  | 1884.64 | 1 | 0 | 992.24 | 0 |
|       | IC   | 1502.74 | 2 | 0 | 833.42 | 0 |
| 2     | 4 × 3 | Org  | 2140.04 | 2 | 0 | 1295.78 | 1 |
|       | IC   | 1195.32 | 3 | 0 | 1390.07 | 2 |
| 3     | 5 × 3 | Org  | 1607.15 | 2 | 0 | 1110.97 | 1 |
|       | IC   | 1784.29 | 3 | 0 | 1015.63 | 2 |
| 4     | 6 × 4 | Org  | 1791.64 | 1 | 0 | 797.31 | 1 |
|       | IC   | 1643.12 | 2 | 0 | 763.27 | 1 |
| 5     | 9 × 6 | Org  | 1229.66 | 3 | 1 | 512.74 | 1 |
|       | IC   | 1101.45 | 3 | 0 | 520.14 | 1 |
| 6     | 4 × 4 | Org  | 1881.96 | 3 | 0 | 1026.94 | 1 |
|       | IC   | 1397.63 | 3 | 0 | 909.71 | 1 |
| 7     | 5 × 4 | Org  | 2000.85 | 0 | 2 | 967.11 | 2 |
|       | IC   | 1131.79 | 3 | 1 | 781.06 | 2 |
| 8     | 5 × 4 | Org  | 1620.59 | 1 | 0 | 1372.07 | 1 |
|       | IC   | 1483.02 | 2 | 0 | 1093.67 | 1 |
| 9     | 20 × 16 | Org | 1218.72 | 3 | 0 | 1495.75 | 2 |
|       | IC   | 1610.02 | 3 | 0 | 1105.69 | 2 |
| 10    | 14 × 10 | Org | 1497.05 | 3 | 0 | 1169.4 | 2 |
|       | IC   | 2419.36 | 2 | 0 | 1450.55 | 2 |
| 11    | 8 × 5 | Org  | 1558.49 | 3 | 0 | 1211.42 | 2 |
|       | IC   | 2310.74 | 3 | 0 | 1659.22 | 2 |
| 12    | 14 × 7 | Org | 1587.6 | 3 | 0 | 1169.4 | 1 |
|       | IC   | 1847.96 | 3 | 0 | 1350.55 | 1 |

Grade 0 = none, grade 1 = < 1/3, grade 2 = 1/3–2/3, grade 3 = > 2/3 of sac.

C = commercials, IC = intracranial model, MV = maximum value on velocity scale (mm/sec), Org = original model, P = Siemens prototype, PF = pathline filling within aneurysm sac, PL = pathline leak which noted only on prototype, Size = size of aneurysm (mm)
In contrast, MV of IC models were faster with models of large aneurysm. IC models had shortened entrance by removal of two artery turns and significant length of the cervical ICA from original model. Our study was motivated by the result of Hodis et al. (6). Contrary to that study, the original models of our study had enough length of cervical ICA, more the five times of their diameter, as suggested by Hoi et al. (5). Ideally, CFD analysis is preferable with enough entrance length and arterial turn. But it is sometimes difficult to get “original model” like this study. Other hemodynamic parameters, including wall shear stress, oscillatory shear index as well as pathline, could be influenced since they are determined by flow velocity. The reversed results of MV with large aneurysm showed similar results in both solutions, except case 9. For figuring out the MV results for large aneurysms, further studies of CFD might be helpful with the real flow conditions at outlet.

Fig. 4. Case 7. 3D virtual rendering image (A) shows kissing artifact (arrowheads) between aneurysm sac and adjacent internal carotid artery (ICA). After removing the artifact by punching tool, 3D surface mesh (B) does not show kissing artifact. Leaking artifact (arrows) is noted on both original (C) and intracranial (IC) model (D). Indeed, pathline filling is poorer than the commercial (not shown) on original model contrast to IC model. Note that no leak between the proximal of ophthalmic artery and adjacent ICA (double arrowheads, A) after the punch out the kissing artifact.
Development of prototype was inspired by vendors due to the increasing clinical interests and publications about CFD. Prototype is a convenient solver which contains the full steps of CFD process, from making 3D images to visualization of CFD parameters. However, it has a limitation of application confined to IC artery obtained by 3D distal subtraction angiography. Attractiveness of the prototype is saving of time and effort by concatenate workflow of each step. There are no concerns regarding the incompatibility of file format, which frequently occurs with commercials. Until now, CFD tools as commercials are not available as a single package of workflow. The purpose of this study was to partly identify similar CFD results between prototype and commercials, because the commercials used in this study are believed to achieve recognition in engineering fields. Analysis in engineering fields requires accurate simulation for manufacturing products. Accuracy is a double-edged sword since it is fussy about variable boundary conditions as well as graphic features of models.

Some limitations or pitfalls are present in this study. First, there were some differences of 2D surface or 3D volume models used by each solver. Second, cutting planes of velocity profile and working angles for pathline did not exactly share the global coordinate with prototype. Third, thin slice source files were obtained from large FOV reconstruction. Large FOV reconstruction results in frequent kissing artifact. 3D model of big sized file produced by small FOV might promise precise mathematical convergence (8). But the 3D model of large FOV gave the appropriate sized data files that are time consuming with ordinary work stations. Fourth, the findings of faster MV in original models were not consistent in the cases of large aneurysms. Subgroup analysis separating the large aneurysms was not possible, due to small number of samples.

There are many algorisms, assumptions and methods to create CFD results. Highly sophisticated methods without assumptions are the best realistic way to simulation. Researchers yield the quietly sophisticated results. Even though many studies have been conducted with model specific resources, model specific data are practically available in few instances. In contrast to engineering, medical fields are limited by shortages of time, equipment, medical expenses and engineering support. Prototype might be a pioneer to provide new tools for clinical decision. But the outcomes could be affected by vessel geometry, especially entrance length. It may also be ideal to use the patient specific velocity profiles at inlet as much as at outlets (9). Further studies might also be directed to identify the major determinant which affects the CFD parameters, as well as be focused on the aneurysm itself.

In summary, the prototype displays the faster flow velocity than commercials with more depiction of pathlines, thereby helping the visualization of flow at the aneurysm. Using the IC model, there was good correlation of MV between both the solvers. Further studies might be needed for different entrance length regarding its influence on the flow at parent vessel or outlets.

Acknowledgments
Sponsored by Siemens AG, Erlangen, Germany.

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프로토타입과 상업용 프로그램을 사용한 전산유체역학의 비교: 뇌혈관 동맥류 모델의 입구 혈관 길이에 따른 차이

박성태1* · 고영배2

목적: 원위부 내경동맥 동맥류의 전산유체역학 분석에서 입구 혈관 길이의 영향을 알아보고자 한다.

대상과 방법: 지멘스의 프로토타입과 상업용 프로그램을 사용하였다. 분석 모델은 3차원 혈관촬영에서 얻은 12개의 원위부 내경동맥 동맥류를 이용하였다. 원형모델은 내경동맥의 경부 분절을 가진 긴 입구 혈관을 가지고 있고, 두개 내 모델은 근위부 혈관분절부 시작하는 짧은 입구 혈관을 가지고 있다.

결과: 프로토타입이 상업용 프로그램에 비해 빠른 최대 혈류값을 보여주었으며, 동맥류 내의 혈류를 가시화한 패스라인을 잘 묘사하였다. 두개 내 모델에서는 두 프로그램 모두 혈류속도가 좋은 상관관계를 보였다.

결론: 원위부 내경동맥 동맥류의 전산유체역학 해석에는 소프트웨어에 대한 이해와 입구 혈관 길이를 고려해야 할 것이다.

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