2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Development of a Virtual Stent Deployment Application to Estimate Patient-Specific Braided Stent Sizes

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Abstract— **A virtual stent deployment application was developed to estimate the appropriate and patient-specific size of a braided stent for patients who undergo endovascular treatment for intracranial aneurysms. Comparing between the simulated deployed and the actual stents, we evaluated the accuracy of the simulation results. Our results indicated that lengths of the virtual and actual stents matched well despite the actual stent being affected by a geometrical change of the parent artery.**

Clinical Relevance—**Surgeons need to be well-experienced to select an appropriate braided stent size for endovascular treatment of intracranial aneurysms, because the actual length of the deployed stent changes. This simulation will be helpful to make tailor-made surgical planning regardless of the surgeons' individual skill level.**

I. Introduction

Subarachnoid hemorrhage (SAH), which occurs after rupture of a cerebral aneurysm, is one of the most common cerebrovascular diseases. Since SAH has a high mortality rate or causes severe disability, some aneurysms are treated by surgical methods in their unruptured state [1]. An aneurysm is an outward bulging pocket filled with blood and located on the cerebral arterial wall. These days, endovascular treatment is a popular surgical treatment method due to its minimal invasiveness [2,3]. Although coil embolization has been widely performed, large, wide-necked, dissecting, and fusiform aneurysms are difficult to treat by coils only [4].

To overcome the shortcomings of coil embolization, a cylindrical device made of metal wires, called a stent, has been developed and widely used to assist the coil mass or to change the blood flow [5,6,7]. A braided stent is one of the most popular types of stents, made by braiding of metal wires of a few tens of micrometer in diameter. Although braided stents contribute significantly to the treatment of aneurysms, selecting the appropriate stent for an individual patient from a lineup of various stent sizes is not easy since the actual length of the stent continuously changes depending on the diameter of the deployed artery (i.e., a stent length becomes longer when it is deployed in a narrow artery compared to when it is deployed in a thick artery). Surgeons need to be well-experienced to select a patient-specific appropriate length during endovascular treatment planning. Currently, the decision makings mostly depend on the surgeons' experience and even intuition. Developing a simulation tool to estimate the stent length after deployment and identify the appropriate stent before endovascular treatment will be helpful to perform safer and more effective treatment regardless of the surgeons' individual skills.

In this study, we developed a new virtual stent deployment application that takes into consideration the geometrical structure of novel braided stents and the diameter of the parent artery. In the development phase of the simulation, the three-dimensional geometry of arteries, including the aneurysm, were reconstructed based on the DSA (Digital Subtraction Angiography)-based images which were acquired before and after the actual stent deployment. Then, the simulation was applied to two illustrative cases to validate the accuracy of the simulation by comparing the simulated with the actual stent length. The stent length estimation error which indicates the difference between simulation and actual were also calculated for quantitative comparison. In addition, geometrical changes of the parent artery before and after stent deployment were examined to investigate the cause of the estimation error.

II. Materials And Methods

A. Patient Selection

The Institution's Ethical Review Board approved all experimental procedures involving human subjects. Two neurosurgeons retrospectively reviewed our database and selected two typical aneurysm cases that were treated with coils and a novel braided stent. To review the versatility of the developed virtual stent, one aneurysm was an ICA (Internal Carotid Artery) aneurysm as an anterior circulation case, and the other was a VA (Vertebral Artery) aneurysm as a posterior circulation case. In both cases, the braided stent was deployed to assist the coil mass.

B. Virtual Stent Deployment Simulation

The patient-specific three-dimensional image data were extracted from 3D-DSA in DICOM (Digital Imaging and Communications in Medicine) format. To apply our original virtual stent deployment simulation software, the DICOM data was imported into the software and we generated the surface data of the aneurysm and artery. In this step, thin arteries under

*Research supported by JSPS KAKENHI Grant Number JP20J30001.

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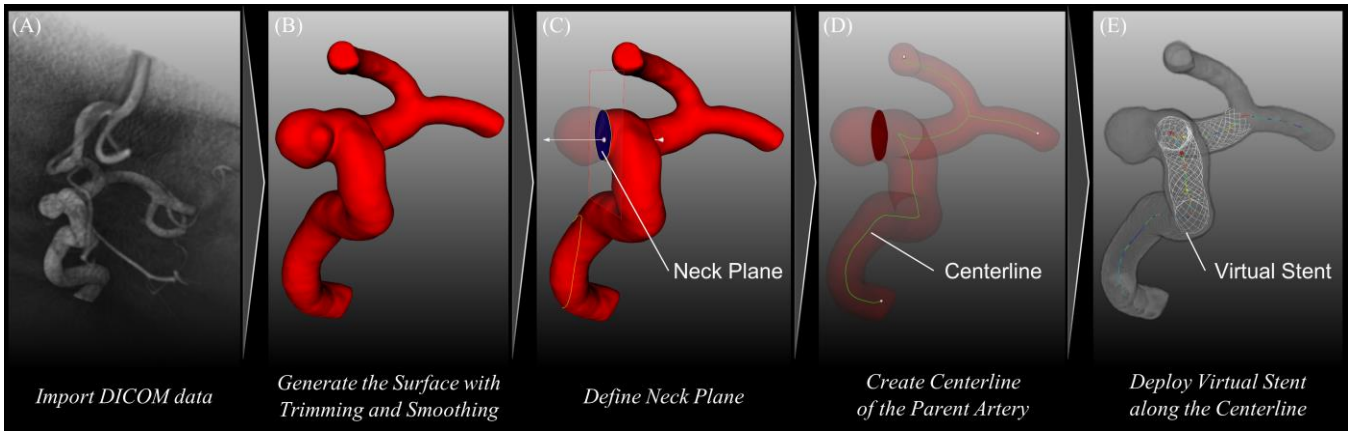

Figure 1. Simulation Process of the Virtual Stent Deployment

the diameter of 1 mm were trimmed and the surface was smoothed. Based on the extracted surface data, an aneurysm neck plane was determined. Since the parent artery was identified by cutting the aneurysm dome with the neck surface, centerlines of the parent artery could be computed. The centerlines were divided in 0.1 mm increments to calculate the average diameter of the artery at a specific point by defining a section orthogonal to the centerline at each division point. Referring to the centerlines and the diameter at each point, a virtual stent was deployed considering its maximum expansion diameter and length at that state (see Fig.1). All the algorisms were installed into our original software.

C. Analysis workflow

First, we extracted the DICOM data of 3D-DSA (unenhanced mask data and subtracted data) before and after stent deployment in the selected illustrative cases. The subtracted data before and after the deployment contained aneurysm and artery. The mask data after the deployment contained stent and coil mass. Since the local coordinate of the image before the deployment does not correspond with that after the deployment, the affine transformation was applied to the data after the deployment to match the coordinates (i.e., all geometries were placed in the same position with the affine transformation). The geometry of the stent and coil was superimposed to the artery and aneurysm that was generated before the stent deployment. Then, we applied the virtual stent deployment simulation to both images acquired before and after actual stent deployment referring to the distal landing position of the actual stent. After the deployment, we measured each stent length determining the proximal and distal endpoint of the stent with the centerline of the parent artery before stent deployment. All the analysis workflow is summarized in Fig. 2.

D. Evaluation Methods

To evaluate the accuracy of the developed virtual stent deployment simulation, we compared the length between simulation and actual stent defining an Estimation Error (*EE*). This parameter is formulated as

$$EE_X = \frac{|L_{virtual\,X} - L_{actual}|}{L_{virtual\,X}} \quad (1)$$

, where the $L_{virtual}$ and L_{actual} are the measured stent lengths of the deployed virtual stent and actual stent, respectively, and the suffix X of *pre* or *post* means before or after the stent deployment, respectively. This parameter indicates the relative error of the virtual stent in the estimation of stent length.

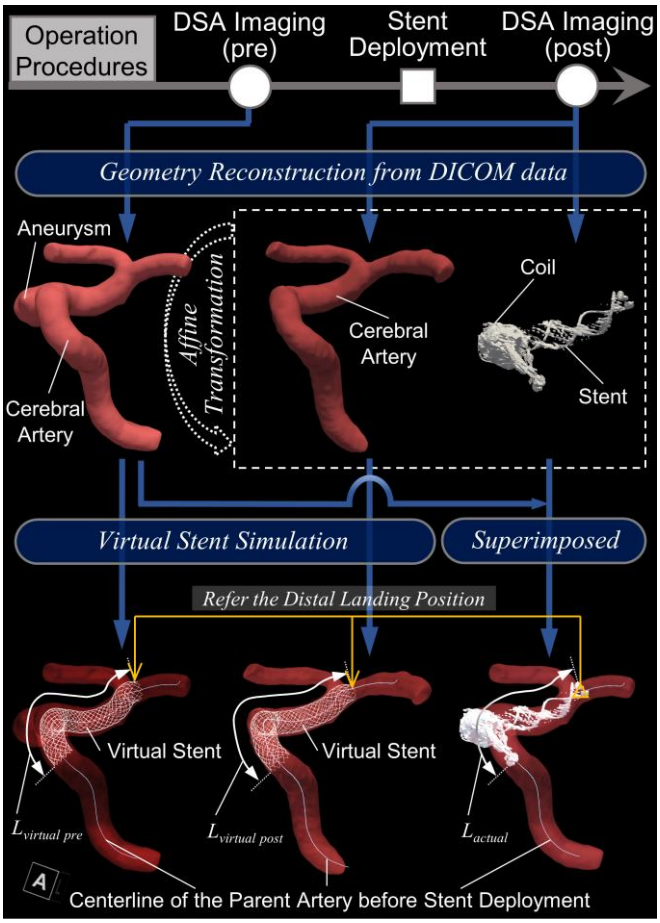

Figure 2. Analysis Workflow to Evaluate the Simulation Results

III. Results

The results of the virtual stent deployment simulation for each illustrative case and image are summarized in Fig. 3. The virtual stents were visualized with white lines in Fig. 3(A), (B), (D), (E). Additionally, the reconstructed geometry of the deployed stent colored with light blue was superimposed on the results of the virtual stent. In these figures, the geometry of the stent contains spherical metal artifacts at the edge created by the radio-opaque stent markers. The geometry also contains

a coil mass since the stents were used to assist coil embolization and the images were acquired after the coil deployment. The geometries of the parent artery were also superimposed to compare the geometrical change between before and after stent deployment. The translucent red and white geometry in Fig. 3(C) and (F) were reconstructed from images before and after stent deployment, respectively (the aneurysms were less enhanced than the vessels because blood inflow was prevented by the deployed stent and coils). To quantitatively evaluate the stent length error between simulation and actual, the detailed values of each stent length and error rate are summarized as *EE* in Table I.

Our results showed that the length of the virtual stent and actual stent matched well with each other in the illustrative ICA case (see Fig. 3(A) and (B)). The quantitative data indicate that the error of the stent length was less than 3% in both (i.e., although the measured length of the actual stent was 26.5 mm, the length of the virtual stent when using the image before and after stent deployment were 25.9 mm with 2.32% errors and 26.3 mm with 0.77% errors, respectively). There was almost no change in geometry before and after stent deployment in the ICA case around the aneurysm, except small change at the distal side of the ACA (Anterior Cerebral Artery)-MCA (Middle Cerebral Artery) bifurcation (see the circled white dashed line in Fig. 3(C)). On the other hand, the results of the illustrative VA case showed a notable error of the length between the virtual stent and actual stent when using the image before stent deployment (see Fig.3(D)). As shown in Table I, the length was 21.8 mm with 16.5% errors while the actual length was 25.4 mm. In contrast, when the image after stent deployment was used to deploy the virtual stent, the error rate reduced to 5.41% as shown in Fig. 3(E) and Table I. The geometry of the parent artery was also visibly changing around the aneurysm before and after stent deployment (see Fig.3(E)).

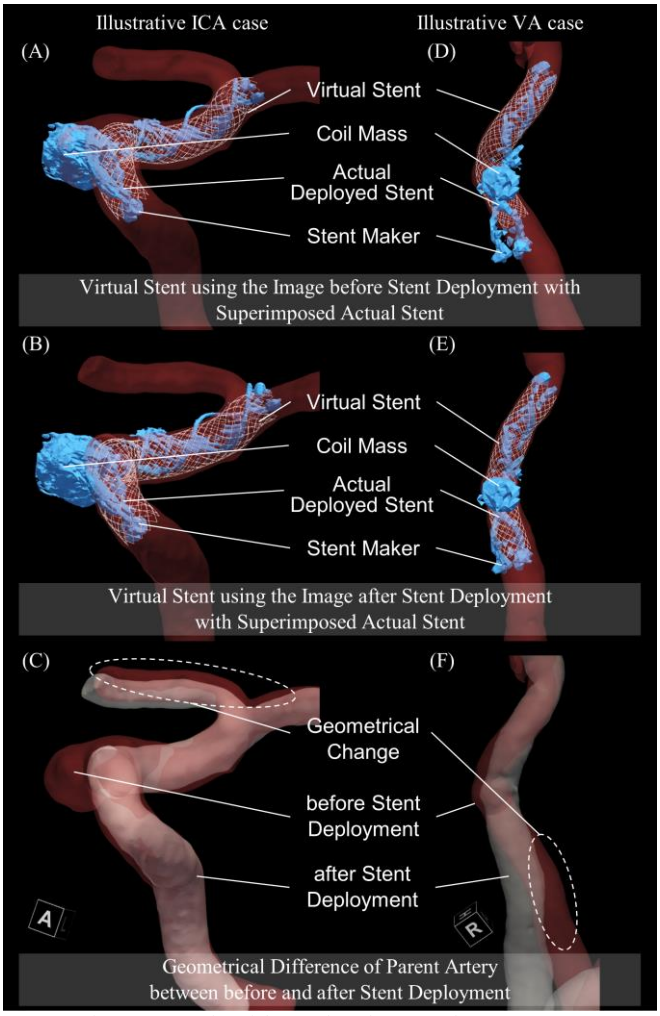

Figure 3. Results of the Deployed Stent and Parent Artery

IV. Discussion

A. The Importance and Difficulty of Appropriate Patient-Specific Stent Selection

The safety and efficacy of endovascular treatment are directly related to the techniques of surgeons. The word "techniques" includes how to choose the appropriate length and diameter of the devices to deploy. From this viewpoint, the braided stent is one of the most difficult devices in terms of identifying the appropriate stent size since the actual length is constantly changed depending on the diameter of the parent artery in which the stent is deployed. Although the first commercial flow diverter stent, Pipeline Embolization Device (Covidien/Medtronic, Irvine, CA, USA), which is one of the typical braided stents, was approved by FDA (Food and Drug Administration) in 2008, no practical and commercial tool has been developed to estimate the patient-specific appropriate stent size considering the actual length of the stent after deployment. The device has been selected depending on surgeons' experience and intuition in most cases. However, if the selected stent is not appropriate for the patient, incomplete stent deployment such as shortening or dislodgement may occur (i.e., the deployed stent may not cover the aneurysm neck completely) [8,9,10,11]. This may not only prevent thrombosis in the aneurysm sac, but it could also cause serious complications such as intraoperative aneurysm rupture or postoperative thromboembolism.

TABLE I. Estimation Error of the Simulated Stent

Case	L_{actual}	$L_{virtual\ pre}$ (EE_{pre})	$L_{virtual\ post}$ (EE_{post})
Illustrative ICA case	26.5 [mm]	25.9 [mm] (2.32[%])	26.3 [mm] (0.77[%])
Illustrative VA case	25.4 [mm]	21.8 [mm] (16.5 [%])	24.1 [mm] (5.41[%])

B. The Estimation Error of the Virtual Stent Deployment Simulation using the Image before the Deployment

To overcome the potential problem of incomplete deployment when using a braided stent, we developed a virtual stent deployment simulation to estimate an appropriate braided stent that takes into consideration the constantly changing diameter of the parent artery. Our results showed that the developed virtual stent deployment demonstrated good correlation with the actually deployed stent even if it uses the image which is acquired before the actual stent deployment as shown in Fig. 3(A) and (D). Especially, in the illustrative ICA case, the simulated stent length ($L_{virtual\ pre}$) and actual stent length (L_{actual}) corresponded well with each other (the error was 2.32%). This finding indicated that this simulation technique can contribute for the surgeons' selection of a

patient-specific appropriate stent length at the stage of endovascular treatment planning. Although the error was 16.5% in the illustrative VA case, it will not be a fatal error, because the absolute error is 3.6 mm, which can be sufficiently adjusted by the surplus of the stent coverage considering that the total length of the stent is around 25 mm.

C. The Estimation Error due to the geometrical changes of the Parent Artery

One of the causes of the estimation error, may be caused by the geometrical change of the parent artery. To verify this assumption, we focus on the results that used the image after stent deployment. As shown in Table I, the errors are smaller compared to when the images before stent deployment were used. More specifically, the errors were changed from 2.32% to 0.77% and from 16.5% to 5.41% in the illustrative ICA and VA case, respectively. The reason for the larger improvement of the error in the illustrative VA case compared to the ICA case is the degree of geometrical change around the aneurysm. In fact, the parent artery became straighter after the stent deployment in the illustrative VA case, but the illustrative ICA case did not show such change. We can also qualitatively identify the improvement of estimation from Fig. 3(D) to 3(E). This geometrical change may be due to the restoring force of the stent. Since the stent is heat-treated during the manufacturing process, it exerts a force to return to the straight and expanded state when it was released from a micro-catheter. Although cerebral arteries are surrounded by various tissues such as parenchyma of the brain, some parts have a certain degree of freedom. Thus, especially in the illustrative VA case, the changed parent artery affects the estimation error when the image before stent deployment was used.

D. Limitations

We demonstrated that the geometrical change of the parent artery will affect the estimation error. However, our simulation did not consider the elasticity of the artery which is needed to estimate the geometrical change before actual stent deployment. In addition, due to metal artifacts, the measured length of the actual stent which is defined as L_{actual} may contain errors since the initial and the endpoint of the stent were visually identified on the centerline of the parent artery. Other virtual stenting methods, such as the active contour model by Zhong et al. and other software, including syngo 3D aneurysm Guidance Neuro (Siemens Healthcare, Forchheim, Germany) or ANKYRAS (Galgo Medical S.L., Barcelona, Spain) were not compared with our software [12]. At this stage, only two cases were selected to evaluate the virtual stent, so a larger cohort study will be needed in the future. Since our software is not commercially available so far, our results have not been objectively evaluated by a third party.

V. Conclusion

We developed a virtual stent deployment simulation application to estimate the deployed stent length in the cerebral artery using 3D-DSA images. Applying the simulation to the illustrative ICA and VA aneurysm cases which were treated with a braided stent and comparing the stent length between simulation and actual, our conclusion may be summarized as follows:

- The estimation error (*EE*) of the stent length showed 2.32% and 16.5% errors for ICA and VA cases, respectively when the images obtained before stent deployment were used.
- The *EE*s were reduced to 0.77% and 5.41% for ICA and VA cases, respectively when the images obtained after stent deployment were used.
- The *EE*s were affected by the geometry changes of the parent artery due to the stent deployment, which has a restoring force to the straight direction.
- If we can estimate the geometry changes of the parent artery before the surgery, we will be able to make tailor-made surgical planning more accurately.

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