New computational fluid dynamics-based method for morphological and functional assessment in cardiovascular skill training

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ABSTRACT
Objective: During cardiovascular surgical skill training, the direct quantification regarding surgical performance is still lacking, including transferring clinically relevant information.

Methods: We introduced a novel computational fluid dynamics-based method in support of vascular surgical hands-on training, which applies continuous self-assessment in vascular anastomoses. The validation of the methodology was implemented in comparing with conventional training courses.

Results: The fifth and seventh consecutive anastomoses of the experimental group showed significantly improved results regarding anastomosis quality when compared with the control group.

Conclusions: Consecutive demonstration of three-dimensional morphology and functional assessment of anastomoses results in improved practical performance among learners regarding anastomosis quality. (J Vasc Surg Cases Innov Tech 2022;8:770-8.)

Keywords: 3D; Anastomosis; Computational fluid dynamics; Objective assessment; Skill assessment; Skill training

Today, vascular surgical education poses major challenges. It has been recently concluded, although the assessment methods have undergone improvement, that the present methods offer only limited objectivity. The limitations of current methods can be summarized as follows: (1) demonstration of the relevance of suturing skills on the outcomes, clinically relevant end points; and (2) only evaluating one-sided results, with no obvious feedback to generate changes of behavior, and therefore, improving technical skills. Currently, the most commonly used assessment method, the Objective Structured Assessment of Technical Skills (OSATS) score, is applied in education and in studies in the field of vascular surgery.

Our research group applies a new method regarding vascular anastomosis quality assessment. The method applies an effective demonstration of a high-definition three-dimensional (3D) model in reference to the vessel structure and presents the simulated blood flow to learners. Notably, it is based on detailed imaging of vessel lumen, computational simulated calculations of blood flow properties, and computational fluid dynamics (CFD). Trainers acquire an overall image of morphology and simulated functionality regarding the vessel structure, allowing them to self-assess the results and alter the technique accordingly in preparation for the upcoming practice session. The educational concept of this methodology is based on encouraging self-observation to learners regarding their potential errors and offering suggestions to every participant.

In the present study, we intend to clarify the potential benefits of this feedback-based training method.

METHODS
A comparative, prospective, and randomized study was recently performed among medical students and residents (both groups were comprised of 10 students [in years 4, 5, and 6 after standard basic surgical technical training] and 10 residents [from the area of general surgery in postgraduate years 1 and 2 after a course on basic surgical operative techniques]). The groups were identical regarding the experience level of the attendees.

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Participants first begin working with 4- to 5-cm long segments of realistic silicone tubes including a 5-mm inner diameter. Every second consecutive segment of anastomoses (first, third, fifth, and seventh) were collected and assessed.

The basic settings, the detailed session, and assistance by course leaders (who were blinded regarding the study and the groups) were completely identical among both groups. In the control group, participants were blinded from seeing the CFD assessment of their efforts; they only received a quick debriefing individually by the course leader as conventionally based on the external appearance of anastomoses and sutures. Learners in the experimental group received detailed results of the CFD analysis no later than the following day with access to a separate online platform including the following: 3D pictures of the lumen of the vessel structure, CFD measurement data, and brief suggestions towards improving the results. Suggestions were given based on the most relevant alteration of the vessel morphology by two independent and experienced observers, who did not take place in the course. Learners also received a brief description in reference to the morphological and functional assessment prior to the beginning of the course (Appendix 2).

The 3D morphological analysis and CFD method were both based on the protocol of lumen 3D scanning and application of standardized in silico examination of vessel specimens (ME3D-Graft Ltd, Hungary). Briefly, the lumen of the specimens were scanned using a high-resolution 3D scanner with a resolution of 10 μm. A self-developed software was applied for computational fluid dynamics using Ansys 20 R1 background (Ansys, Inc, Canonsburg, PA), applying standardized and physiological boundary conditions and meshing algorithms.

The first phase in blood flow simulation was elongation of virtual models (SpaceClaim, Ansys Inc). Next, volume meshing was performed, resulting in a high-quality mesh. For blood modeling, a dynamic viscosity parameter was used, and boundary conditions were generated; the inflow artery to the bypass had no stenosis. The distal anastomosis of the bypass was placed on the artery distal to a 75% stenosis to simulate a clinical scenario, when a significant stenosis or obstruction requires a bypass to assure adequate distal perfusion. The outflow vessel distal to the anastomosis had normal vascular resistance. Imagery from all angles depicting the vessel structure were saved and forwarded to the participant representing the following parameters: energy loss, pressure drop, and WSS are demonstrated in Fig 4.

### RESULTS

The most frequent variations and morphological changes are demonstrated in Fig 1. Fig 2 shows how two representative participants in the two groups changed their surgical technique while performing the anastomosis.

Results of the measurements are demonstrated in Table.

#### Energy loss.

Energy loss through the anastomosis structure decreased gradually in both groups with a significant difference during the seventh anastomosis compared with the onset (first anastomosis) value. In reference to the fifth anastomoses, the intergroup difference was notably significant (Fig 3).

#### Energy efficiency.

Energy efficiency increased gradually in both groups from the first anastomosis to the seventh anastomosis. In comparing the first and seventh anastomoses, significant differences were obtained among both groups.

#### Pressure distribution—pressure drop.

The general observation was in identifying the difference between inflow and outflow pressures, which gradually decreased among both groups. Compared with the first vessel specimen to the seventh anastomosis, significant differences were clearly observed among both groups.

#### The proportion of distal and proximal pressures.

In demonstrating pressure mapping within the structures, a fractional flow reserve (FFR) map-like appearance was generated. In both groups, the values of FFR demonstrated the tendency to increase. A significant difference was observed between the control and experimental group with regards to both the fifth (P < .05) and seventh anastomoses (P < .1).

#### Wall shear stress.

In measuring shear forces, normal and low values of wall shear stress (WSS) in the form of a percentage regarding the overall area of the anastomosis region were measured and compared with both groups.

The low WSS area was stagnant, with a tendency to decrease in consecutive anastomoses. In the experimental group, the values of the seventh anastomoses were significantly lower when compared with the first anastomoses.

The comparison in both the first and seventh anastomoses among the two groups with regard to energy loss, pressure drop, and WSS are demonstrated in Fig 4.

### DISCUSSION

Validation and reflection in surgical performance are crucial for the assessment, training, and improvement regarding surgical finesse and expertise. In applying an unusual number of morphological and CFD analyses.
our study demonstrates how feedback regarding the functional and morphological aspects of anastomoses assures improvement in surgical performance.

Today, the assessment methods are often based on instructors’ opinions or some predefined scoring. However, several evaluation methods still apply in reference to an assessment of the various movements or external observation regarding the procedure performed by a participant, yet the applied methods fail to demonstrate how surgical techniques can influence the healing of tissues and organ integrity. Although the OSATS score is an easy-to-access and cost-effective method, it has neither objective results-based assessment nor predictive scoring regarding clinical results; moreover, it requires the presence of one or more additional evaluators. As the most objective and mathematically obtainable solution in support of regarding an assessment of anastomoses, transit-time flow measurement is also applied during microvascular and vascular hands-on training. However, it is less widely applicable in surgical education, and the results are highly dependent upon the conditions and circulation of experimental animals.

Several attempts have been made to objectively measure and compare end results of simulated surgical procedures by the reflection of end results of participants’ activity. Scales were applied for dichotomous assessment of patency implementing a visual assessment; moreover, several studies describe the importance regarding anastomosis morphology on functionality. CFD is a widely applicable and tried tool in the field of vascular surgery, as represented by the exponential number of articles referencing the topic. CFD-based studies have recently formed one of the most downloaded articles in European Journal of Cardiovascular Surgery journals, representing the professional interest in that field. Simple and complex simulation is an increasing role in surgical skill training. CFD is used

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**Fig 1.** The most frequent morphological changes in end-to-side anastomoses of 5 mm vessel imitations that appeared in the study (160 consecutive anastomoses). The representative side-view pictures are presented as the sequence of its frequency: A, Too deep heel stich is present. The anastomosis upstream angle received a stitch that integrates too much tissue from host and/or graft vessel. B, Purse-string sign. The suture density or the tightness of suture row exceeded the optimal level, so circumferentially there is a narrowing at the level of anastomosis. C, Short arteriotomy of host vessel. Too short arteriotomy resulted in relative narrowing of the structure at the level of anastomotic suture. It is caused by the low area of anastomosis at host or also by the imbrication of graft tissues (the suggestion is dependent on the type of the morphological alteration here). D, Too deep toe stich. The anastomosis downstream angle received a stitch that integrates too much tissue from host and/or graft vessel.
Fig 2. How two representative attendees changed/improved their surgical technique in performing anastomosis. **A**, Series of anastomoses from one attendant of the control group. **B**, Series of anastomoses from one attendant of the experimental group. The number at the right bottom corner of each picture means the consecutive number of anastomoses performed by persons during the study.
in clinical practice in the case of aortic dissection, aortic aneurysm, and in stent graft treatment. This tool is capable of determining the FFR and is capable in the design of effective surgical procedures.

In this present study, we aimed to implement an objective and standardized protocol regarding the evaluation system. Our data highlights the importance of self-assessment in performance and striving for optimal results.

Table. Main computational fluid dynamics (CFD) parameters of anastomoses sutured by residents and students, Department of Surgical Research and Techniques, University of Pécs, 2019-2020

| Group | First anastomosis. mean (SD) | Third anastomosis. mean (SD) | Fifth anastomosis. mean (SD) | Seventh anastomosis. mean (SD) | % (seventh/first) |
|-------|-----------------------------|-----------------------------|-------------------------------|-------------------------------|------------------|
| Energy loss | A 0.274 (0.093) | 0.212 (0.034) | 0.207 (0.028) | 0.204 (0.039) | 74.45 |
|       | B 0.274 (0.095) | 0.205 (0.062) | 0.186 (0.013) | 0.188 (0.025) | 68.61 |
| Energy efficiency, % | A 96.944 (1.128) | 97.88 (0.4) | 97.926 (0.696) | 97.885 (0.709) | 100.97 |
|       | B 96.611 (1.402) | 97.515 (1.156) | 97.97 (0.421) | 98.134 (0.074) | 101.57 |
| Pressure drop | A 261.075 (99.64) | 177.529 (34.914) | 167.454 (16.542) | 175.416 (27.327) | 67.18 |
|       | B 250.855 (88.521) | 184.165 (29.394) | 162.003 (32.556) | 164.465 (23.165) | 65.56 |
| FFR | A 0.785 (0.042) | 0.808 (0.029) | 0.817 (0.016) | 0.821 (0.024) | 104.58 |
|       | B 0.781 (0.038) | 0.807 (0.034) | 0.829 (0.019) | 0.836 (0.023) | 107.04 |
| Area of normal WSS, % | A 31.796 (9.348) | 33.172 (7.568) | 33.141 (6.56) | 35.269 (8.229) | 110.92 |
|       | B 30.711 (7.617) | 31.235 (5.799) | 34.413 (9.234) | 37.096 (6.479) | 120.79 |
| Area of low WSS, % | A 32.249 (12.058) | 30.489 (10.798) | 30.915 (7.88) | 29.998 (7.129) | 93.01 |
|       | B 32.582 (7.58) | 31.074 (5.705) | 30.301 (7.735) | 27.406 (6.34) | 84.63 |

FFR: Fractional flow reserve. Group A, control group; Group B, experimental group; SD, standard deviation; WSS, wall shear stress.

*Significant difference comparing the first with the final anastomosis (P < .05).

bSignificant intergroup difference (P < .05).

cRegarding FFR of seventh anastomosis, the intergroup difference was significant (P < .1).

Fig 3. General parameters of anastomosis function are presented comparing the two groups. Values of energy loss (A) and proportion of distal and proximal pressure (B) were compared in two groups. The numbers on axis x represent the sequential anastomoses (the first, third, fifth, and seventh anastomoses are demonstrated) performed by attendees of two experimental populations. Empty bars represent the control; gray bars demonstrate the group getting continuous support of three-dimensional (3D) morphological and functional feedback.

*P < .05 between first anastomosis of the similar group. #P < .05 between two groups. ##P < .01 between two groups.
In demonstrating the functional importance regarding morphological observations, CFD results were effectively evaluated and thoroughly assessed. In the present study, an exceptional number of CFD analyses were investigated, focusing on parameters that specifically represent the overall, general characteristic of vessel structures. Overall fluid characteristics of anastomoses were shown with pressure distribution, WSS, energy loss, and efficiency of the structure.

It is unknown how the study group improves the quality of procedural performance following eight anastomoses; thus, exact formative learning mechanisms of the skills need further investigations. Although there is an improvement in performance in both groups, a large number of consecutive anastomoses should be evaluated to prove the statistical advantage of our novel method. The methods employed can offer a high approximation to realistic situations; however, we used a simplified CFD methodology and morphological assessment for comparison regarding individual performance using standardized methodology.

The methodologic background in support of the technology is not available to every course provider. However, the preparation of vessel specimens can be performed in 3 minutes, and cost estimations demonstrate that analysis can be performed valued at approximately 30 to 50 Euros. Results can be achieved on-site within 40 minutes and within 24 hours from any location. It includes carrying and the full workflow analysis. On the other hand, hardware elements can be applied in any center, making the method of analysis more affordable and cost-effective.

In summary, we believe the method using analysis of blood flow and morphology in skill training can serve as an effective tool in the professional assessment and evaluation regarding competencies and can lead to effective improvement in skill training.

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Fig 4. The changes/improvement of first and seventh anastomoses are compared in two groups. The improvement of given value is calculated relative to the value of the first anastomosis and presented as %. Empty circles represent the controls, gray circles demonstrate the group getting continuous support of three-dimensional (3D) morphological and functional feedback. A, Energy loss. B, Pressure drop through the anastomosis. C, Area of “normal value of wall shear stress (WSS)” on the wall of anastomoses (These parameter values were demonstrated as below and above the value of a given cut off. It resulted in a population of 160 vessels. The distribution of this population of vessels were further considered to determine the cut off values of WSS. The WSS value was considered to be high when its value was in the upper 20th percentile of the entire population (WSS value, 6138 Pa) and was considered to be low if the value was below the 20 per centiles (WSS value, 1.91 Pa). Area of low, normal, and high WSS regions were determined according to these cutoff values as a proportion of entire structure). The values were measured on standardized segment of anastomosis.
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APPENDIX 1

Definition of terms and application in our study

Energy efficiency is calculated as the ratio of outgoing and incoming energy.

Energy loss is calculated as the difference of incoming and outgoing energy.

FFR: Fractional flow reserve (FFR) is a technique used in coronary catheterization to measure pressure differences across a coronary artery stenosis to determine the likelihood that the stenosis impedes oxygen delivery to the heart muscle.

Pressure distribution-pressure drop: The average of two inflow profile-pressure measurements was divided by the inflow profile pressure at the same time-step. The general observation was that the difference in between inflow and outflow pressures decreased generally and gradually in both groups.

Proportion of distal and proximal pressures: For demonstrating pressure mapping in the structures, having a fractional flow reserve map-like appearance, low resistance profile was applied on the outflow tract.

WSS: Wall shear stress. For measuring shear forces, normal and low values of WSS were measured and compared in both groups.

APPENDIX 2

Study design

From January 2019 to May 2020, a comparative, prospective, and randomized study was performed among medical students and residents in the Department of Surgical Research and Techniques, University of Pécs, Hungary. The attendees were fourth- to sixth-year medical students participating in an elective, advanced surgical course and first- and second-year residents during a compulsory course for surgical skill improvement. Students had a compulsory practical course on surgical technique before (in the third year). Residents were from an all-general surgical specialty area. Before the study, they had a 1-week-long hands-on training of basic surgical techniques, for suture techniques, handling, and minimally invasive methods. Cardiac and vascular residents were excluded from this study.

Courses lasted 6 weeks, weekly 1.5 hours of training for students. For residents, the training was daily for 1.5 hours for 4 days.

Both groups had 10 students and 10 residents; thus, the groups were identical regarding the experience level of the attendees. Because we observed that vascular residents have more stable higher performance in general, cardiac and vascular residents were excluded from this study. The basic settings, the detailed session, and assistance by course leaders were completely identical in the two groups.

Before the course, learners had compulsory practical training on basic surgical techniques such as tissue handling, knot tying, instrument application, etc. Learners also received a brief description in reference to the morphological and functional assessment. Participants first begin working with 4- to 5-cm long segments of realistic silicone tubes. After completion, every second consecutive segment of anastomoses (first, third, fifth, and seventh) were collected and assessed.

In the control group, participants were blinded from seeing the results of their efforts; they only gave the specimen for analysis according to their approval. After every anastomosis, a quick debriefing was performed individually by course leader as a convention. During that debriefing, the anastomosis was visually inspected, and the opinion and suggestion were reported to the participant. Also, participants have the possibility to pose questions about methods for improving technique.

Learners in the experimental group sent the performed anastomosis for assessment after finishing and received the results no later than the following day, with access to a separate online platform. The results included the following: three-dimensional pictures of the lumen of the vessel structure, computational fluid dynamics measurement data, and brief suggestions towards improving the results were all offered. Suggestions were given based on the most relevant alteration of the vessel morphology by two independent and experienced observers, who did not take place on the course.

APPENDIX 3

Detailed description of the methodology of the assessment

The three-dimensional (3D) model of vessels: After completion the anastomoses, specimens were prepared for YourAnastomosis (ME3D-Craft ltd, Hungary), a standardized method for presenting a high-resolution virtual 3D model of vessels. First, the specimens were filled and de-aired with low-viscosity resin. Thereafter, pressure was maintained on 120 mmHg until polymerization occurred. The original vessel imitations were removed from the resin mold. The molds were scanned using a high-precision strip-light scanner. The model underwent a standardized and protocol-based improvement using open-source software (Meshmixer, Autodesk Inc; Geomagic Wrap, 3DSystems Inc)

Blood flow simulation. After elongation of the virtual models (elongation with four times the diameter) (SpaceClaim, Ansys Inc), volume meshing was performed, resulting in a high-quality mesh with at least 300,000 cells. For simulation, the dynamic viscosity parameter was used for blood modeling, and boundary conditions were generated as follows: host artery inflow received a modified velocity profile mimicking 75%
stenosis of the artery. A time-dependent velocity profile was calculated for modeling the graft artery inflow. The outflow of the vessel structure had a dynamic resistance, mimicking vascular resistance of 185 dyn.sec.cm$^{-5}$. On these models, standardized computational fluid dynamics (CFD) was carried out (ANSYS 19 R1 software, Ansys Inc). Variables including low velocity, pressure distribution, wall shear stress, strain, flow helicity, vorticity, Reynolds number and calculated parameters of oscillating shear index, wall shear stress spatial gradient, time average wall shear stress spatial gradient, relative residence time, resistance, and energy loss were calculated.

Two independent and skillful course leaders (uninvolved in the course) acted as observers and evaluated the pictures. The most severe/important alteration was selected and used for forming suggestions. Pictures from all sides of the selected vessel structure were sent to the attendee. Participants also received short and comprehensible suggestions to improve their work.

Our team performed 160 detailed and standardized CFD analyses evaluating the following parameters: energy loss, energy efficiency, pressure distribution-pressure drop, proportion of distal and proximal pressures, and wall shear stress. The time required for CFD simulation is about 40 minutes. After simulation, the calculation of fractional flow reserve needs a few more minutes. An information technology specialist performs the process on our team.