Patency of separate tube grafts for intercostal artery reconstruction: Size and length matter

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Norihiko Shiiya, Naoki Washiyama, Daisuke Takahashi, Kazumasa Tsuda, Yuko Ohashi, Kayoko Natsume, Masahiro Hirano, Yuki Takeuchi

First Department of Surgery, Hamamatsu University School of Medicine, Hamamatsu, Japan

Corresponding author; Norihiko Shiiya

First Department of Surgery, Hamamatsu University School of Medicine

1-20-1, Handayama, Higashi-ku, Hamamatsu 431-3192, Japan

TEL: +81-53-435-2276, e-mail: shiyanor@hama-med.ac.jp

The manuscript was presented at the 36th EACTS annual meeting in Milan on 6 October, 2022.

Word count: 4158 words

Visual abstract

Key question: What is the optimal size and length of the separate tube grafts for intercostal artery reconstruction?

Key findings: For lengths <25 mm, 8- and 10-mm grafts showed better patency than 12-mm grafts in thoracoabdominal aortic replacement.

Take-home message: Size and length influence intercostal artery graft patency. Computational fluid dynamics seem useful to pursue optimal graft design.

Abstract

Objectives. Low patency is a major concern when using separate tube grafts for intercostal artery reconstruction. We aimed to elucidate the optimal size and length of grafts from the patency and computational fluid dynamics.

Methods. The patency, size, and length of separate tube grafts were evaluated in 41 patients. Computational fluid dynamics simulation was performed in a model derived from a patient with a patent 12-mm graft of 15 mm in length, with 2 simulation models with a smaller (8-mm) or longer (30-mm) graft.

Results. A total of 49 grafts were used for intercostal artery reconstruction. There was 1 in-hospital death and 2 spinal cord injuries. The patency rate, which could be evaluated in 46 grafts, was 63% (29/46). It was 71% (24/34) in thoracoabdominal aortic replacement and 42% (5/12) in descending aortic replacement. Among 14 patients in whom all grafts were occluded, no patients developed spinal cord injury. All grafts longer than 25 mm were occluded (n=5). Eight- and 10-mm grafts showed better patency than 12-mm grafts in thoracoabdominal aortic replacement (p=0.008), when grafts were shorter than 25 mm. Computational fluid dynamics simulation revealed vortical flow within the 12-mm graft, which did not reach the intercostal orifice, while helical flow was maintained throughout the cardiac cycle within the 8-mm graft.

Conclusions. Eight- and 10-mm grafts seemed better than 12-mm grafts, and grafts should be kept shorter than 25 mm. Computational fluid dynamics simulation may shed light on the issue of optimal intercostal artery reconstruction technique.

Keywords: spinal cord protection, aortic surgery, intercostal artery reconstruction, patency

Abbreviations and acronyms

CT: computed tomography, CFD: computational fluid dynamics, SD: standard deviation, Q1: first quartile, Q3: third quartile

Introduction

Intercostal artery reconstruction has been used to reduce the risk of ischemic spinal cord injury [1, 2]. Although the island patch technique has been widely used, it is associated with the long-term risk of patch aneurysm formation, especially in patients with connective tissue disorder [3-6]. To avoid such a complication, various techniques have been proposed, including the use of separate tube grafts [4-7]. However, low graft patency is a major concern when separate tube grafts are used as end grafts [4-7].

To improve patency, our recent practice is to keep grafts as short as possible and to use larger grafts [7] to make the aspect ratio close to 1:1. We conceived of this idea based on the findings of follow-up computed tomography (CT) after aortic arch surgery, which almost invariably showed contrast enhancement of the remnant of suture-closed side-arm grafts, and the aspect ratio of the remnant was nearly 1:1. We hypothesized that this was due to persistent vortical flow within the remnant during the entire cardiac cycle and, by making the aspect ratio close to 1:1, we can maintain vortical flow within the separate tube grafts for intercostal artery reconstruction.

In this study, we aimed to elucidate the optimal size and length of tube grafts based on the patency, and the difference in flow dynamics in relation to size and length by the computational fluid dynamics (CFD) simulation.

Patients and Methods

Ethical statement

This study was conducted in accordance with the Declaration of Helsinki and was approved by our institutional review board (December 26, 2022; 22-154). The need for individual informed consent was waived, as this study was a retrospective analysis of data collected for routine care.

From 2009 to November 2022, we performed 162 descending (n=69) or thoracoabdominal (n=93) open aortic replacement procedures. The study subjects consisted of 41 of 162 operations in which separate tube grafts were used for intercostal artery reconstruction. In the remaining patients, intercostal arteries were not reconstructed in 75 cases (descending: n=43, thoracoabdominal: n=32), intercostal arteries were preserved by beveling an aortic suture line in 44 cases (descending: n=13, thoracoabdominal: n=31), and intercostal arteries were reattached using the patch technique in 2 cases (descending). The patency and graft length were evaluated by post-operative multi-slice CT (Figure 1). The grafts were judged to be patent when the contrast enhancement of the reconstructed arteries could be traced from the grafts. The graft size was retrieved from operative records.

Technique of intercostal artery reconstruction

We have been performing multi-segmental sequential intercostal artery reconstruction, which we believe will reduce the incidence of spinal cord ischemia during reconstruction [7-9]. The rationale is to maintain collateral blood flow through the epidural network that is present between the neighboring intercostal arteries [7-11]. Briefly, we limit the number of intercostal arteries clamped at one time, and maintain blood flow to the neighboring arteries, which was achieved by sequential reconstruction of the intercostal arteries and distal aortic perfusion. We always perform monitoring of motor-evoked potentials to verify that collateral blood flow to the spinal cord is sufficient. When spinal cord ischemia is detected during intercostal artery reconstruction, every effort is made to improve the spinal cord blood flow, which includes augmenting the proximal and distal aortic pressures, blocking back bleeding from the arteries, and selective intercostal artery perfusion. Intercostal artery reconstruction is not scheduled when the feeding arteries, preoperatively localized by multi-slice CT, are not included in the extent of repair;

however, reconstruction is added when neuromonitoring shows unexpected ischemic changes.

When multi-segmental intercostal artery reconstruction is not feasible, we use bidirectional perfusion with moderate hypothermia. Deep hypothermia is reserved for those undergoing open proximal aortic anastomosis, which is frequently the case in chronic aortic dissection with aortic arch involvement.

Technically, we secured separate tube grafts to the aortic wall without creating a button. We placed 3 to 4 mattress sutures and tied them down to create the bank of native aortic wall. We then added running sutures passing through the bank, between the mattress sutures (Figure 2). Subsequently, the grafts were connected to the main graft to achieve the shortest branch graft length. We also avoided paired reconstruction to prevent kinking when they were wide apart. Care was taken not to allow the steal phenomenon; this was achieved with the use of an occlusion catheter or by clamping the graft once it was secured to the aortic wall.

CFD

CT data of a patient with a patent 12-mm graft, with a length of 15 mm, were used to create a model for CFD. Two simulation models were created with a smaller (8-mm) graft or a longer (30-mm) graft. The details of the CFD method have been reported previously

[12]. Briefly, image data in the Digital Imaging and Communications in Medicine format were transferred into 3-dimensional patient-specific geometries, and computational meshes were created. Cardiac output was set at 5.0 L/min and the heart rate was set at 60 beats/minute. For turbulent pulsatile flow simulations, an CFD finite volume solver and RNG k-epsilon models were used. The blood density was set at 1060 kg/m^3 and the viscosity was set at 0.004 kg/m/s. All data analyses were outsourced to the Cardio Flow Design Inc (Tokyo, Japan; http://cfd.life/).

Statistical analyses

All statistical analyses were performed with the SPSS statistical package version 25 software program (SPSS Inc., Chicago, IL, USA). To compare the differences between the 2 groups, Fisher’s exact test or Pearson’s chi-squared test were used for categorical variables and the Mann–Whitney U-test was used for continuous variables that followed non-normal distribution. P values of <0.05 were considered statistically significant. The mean and standard deviation (SD) were used to express results that followed normal distribution, and the median, first quartiles (Q1), and third quartiles (Q3) for those following non-normal distribution.

Results

The mean age of the patients was 60 (SD 9.9) years (range 38 to 74 years). Thirty-four patients were male. Six operations were non-elective, 2 operations were performed for rupture. The patient characteristics are summarized in Table 1. Of note, 12 of the 30 patients who underwent thoracoabdominal aortic replacement had a history of descending or thoracoabdominal aortic replacement, and extent-II replacement was completed in 10 of these patients. This reflected our preference for staged aortic replacement in chronic aortic dissection. Two patients had a history of thoracic endovascular aortic repair. Deep hypothermia was used in 9 of 11 patients who underwent descending aortic replacement, and 8 of the 9 patients had chronic aortic dissection. A total of 49 grafts were used for intercostal artery reconstruction. The grafts were connected to a pair of intercostal arteries in 19 cases and to a single artery in 30 cases. The mean number of grafts per patient was 1.2.

Spinal cord feeding arteries were identified preoperatively in 33 patients (80%), and separate tube grafts were connected to these arteries in 18 patients. Among the remaining 15 patients, 11 patients underwent reconstruction of the neighboring arteries instead of the feeding arteries, based on the results of neuromonitoring, because the local condition was not suitable for reconstruction. The feeding arteries were not included in the extent of replacement in 2 patients and were supplied through collateral pathways in 2 other patients.

Operative outcomes

There was 1 in-hospital death (1/41; 2.4%) and 2 spinal cord injuries (2/41; 4.9%). The cause of death was rupture of a remote penetrating ulcer in the aortic arch. Spinal cord injury occurred in a patient with rupture and in another patient who underwent a deep hypothermic operation for chronic aortic dissection.

Graft patency

Graft patency could be evaluated in 46 grafts in 38 patients, and showed that 29 grafts (63%) were patent. The patency was comparable between the grafts connecting to a pair of intercostal arteries (56%; 10/18) and those connecting to a single intercostal artery (68%; 19/28). It was also comparable between those connecting to the spinal cord feeding artery (67%; 12/18) and those not connecting to the spinal cord feeding artery (61%; 17/28). The patency rate in thoracoabdominal aortic replacement was 71% (24/34), while it was 42% (5/12) in descending aortic replacement. Similarly, the patency rate was 72% (23/32) in patients who underwent surgery under distal aortic perfusion or bidirectional perfusion, while it was 43% (6/14) in patients who underwent deep hypothermic operations. It was comparable between first-time thoracoabdominal replacement (68%; 13/19) and redo operations (73%; 11/15). One of the 26 patients with a patent graft developed paraplegia, while none of the 12 patients in whom all the grafts were occluded developed spinal cord injury.

Patency according to the size and length of the grafts is shown in Figure 3. There were no differences in patency between the 8-, 10-, and 12-mm grafts (9/14, 9/12, and 11/20, respectively). The graft length (mm) was comparable between the patent grafts (median 15.0, Q1 12.5, Q3 18.0) and the occluded grafts (median 17.0, Q1 12.0, Q3 28.0). All the grafts longer than 25 mm were occluded (n=5), while all 10-mm grafts shorter than 20 mm were patent (n=9). As far as the grafts shorter than 25 mm that were used in the thoracoabdominal aortic replacement were concerned, all 10-mm (n=8) and 8-mm (n=8) grafts were patent, while the patency rate of the 12-mm grafts was 53% (8/15) (p=0.008) (Figure 4).

CFD (Figure 5, Video)

In the original model (φ12 mm, length 15 mm), vortical flow was generated within the branch graft, which did not reach the intercostal orifice. In simulation-1 (φ8 mm, length 15 mm), helical flow was maintained within the branch graft throughout the cardiac cycle. In simulation-2 (φ12 mm, length 30 mm), a second vortex was formed during diastole, which made a limited contribution to the intercostal flow.

Discussion

The patency rate of intercostal arteries reconstructed by separate tube grafts has been reported to be low, ranging from 31% to 70% [4-7]. In addition, several authors have reported that graft occlusion was associated with ischemic spinal cord injury [4-6]. Therefore, several other techniques have also been proposed to improve patency and to prevent patch aneurysm formation, including the single-branch patch, loop graft, and parallel graft, with patency rates ranging from 77% to 86% [5, 6, 13, 14].

We have been using separate tube grafts as end grafts not only to prevent patch aneurysm formation but also to enable multi-segmental sequential intercostal artery reconstruction [7-9]. The use of a separate tube as an end graft is optimal for this technique, while the single-branch patch technique may be difficult due to the proximity of the clamp. Perfusion of the downstream neighboring arteries is not possible when the loop or parallel grafts are used because several pairs of intercostal arteries need to be clamped at one time. In our experience, multi-segmental sequential intercostal artery reconstruction reduced the incidence of ischemic spinal cord injury and the prevalence of ischemia during intercostal artery reattachment, as detected by neuromonitoring [8, 9].

The overall graft patency rate of 63% was lower than that in our previous study (70%) [7]. The difference was especially notable when grafts connecting to the feeding arteries were concerned (67% vs. 91%). This difference may be explained by the difference in patient characteristics. Our previous study was limited to patients undergoing thoracoabdominal aortic replacement. In addition, as we introduced the concept of staged aortic replacement for chronic aortic dissection in 2009, fewer patients underwent extent-II repair and there were more patients with a history of previous descending aortic replacement in the present study, in comparison to our previous study. This was reflected in the mean number of involved segments, which was 8.0 in the present study and 9.3 to 9.6 in our previous study [7]. In descending aortic replacement, the mean number of segments involved was 7.7 and the T11 and T12 intercostal arteries were spared in 10 of the 11 patients. Therefore, the reconstructed intercostal artery may have been provided with more collateral blood flow from these arteries and the flow demand may have been lower, which may explain the lower patency in descending aortic replacement. Indeed, the graft patency rate in thoracoabdominal aortic replacement was 71%, which was comparable to that in our previous study. Similarly, flow demand to the intercostal arteries supplying the spinal cord may have been reduced by the staged replacement strategy, since it augments the development of collateral pathways.

Regarding the graft design, the present study clearly showed the importance of graft size and length. Contrary to our hypothesis that an aspect ratio near 1:1 would be optimal, 12-mm grafts were not better. The results of the CFDsimulation provided some basis to explain this result. When a 12-mm graft was used, vortical flow was generated within the branch graft, as expected. However, this may not contribute to graft patency because the vortex does not reach the intercostal artery orifice, even with a graft length of 15 mm. When the graft length was changed to 30 mm, a second vortex was generated, which made a limited contribution to the intercostal flow. On the other hand, helical flow was maintained throughout the cardiac cycle when the graft diameter was changed to 8 mm. For grafts shorter than 25 mm, the patency rate of 8-mm and 10-mm grafts was 100% and was significantly better in comparison to the 12-mm grafts, as far as the patency in thoracoabdominal aortic replacement was concerned. Therefore, we speculated that persistent helical flow during diastole was beneficial in the presence of size discrepancy between the graft and the intercostal artery, and helical flow may also be present within the 10-mm graft. This situation is completely different from that of coronary artery bypass grafting, in which the laminar flow is maintained within the graft.

Although the patency of reconstructed intercostal arteries seemed lower than that after island patch reconstruction, graft occlusion was not associated with ischemic spinal cord injury in either the present study or our previous study [7]. This is in clear contrast to the studies showing an association between graft occlusion and spinal cord injury [4-6]. This difference could be explained by our use of multi-segmental sequential intercostal artery reconstruction guided by neuromonitoring. Using this strategy, we could reduce the prevalence of spinal cord ischemia during reconstruction (as detected by neuromonitoring) to 10% after effective control of back-bleeding [9]. Therefore, we could notice reconstruction failure by neuromonitoring if it led to spinal cord ischemia, and could either revise or add intercostal artery reconstruction as necessary. In fact, the only spinal cord injury among the elective operations developed in a patient who underwent a deep hypothermic thoracoabdominal aortic operation, in which neuromonitoring was not useful until full rewarming. In this case, additional intercostal artery reconstruction, which was proven to be patent postoperatively, could not be performed before the injury became irreversible.

The result that graft occlusion was not associated with ischemic spinal cord injury may also mean that the patency of tube grafts is not necessary to avoid spinal cord injury, as they remain patent for sufficient time to allow the development of new collateral pathways.

Given the results of the present study, we are changing our strategy to use the single-branch patch technique in patients undergoing deep hypothermic operations. This is because the patency in this group of patients (most of them underwent descending aortic replacement) was low, and cannot be evaluated by neuromonitoring until full rewarming.

In addition, reconstruction using the patch technique is not difficult in deep hypothermic operations because there were no clamps in close proximity. Although graft occlusion in descending aortic replacement did not result in spinal cord injury, possibly because of the presence of collateral blood flow through the distal intercostal arteries, long-term patency of the reconstructed intercostal arteries may reduce the risk of spinal cord ischemia during the second stage downstream operation, which is anticipated in patients with chronic aortic dissection.

Finally, CFD analyses may also be useful for the loop graft and parallel graft techniques for intercostal artery reconstruction. Since the inflow and outflow of the graft are created on the main aortic graft in these techniques, there are no pressure gradients between the main and branch grafts across the 2 anastomotic sites. In this situation, the flow pattern within the graft may be highly variable, depending on the difference in the propagation of pulse waves between the main and branch grafts. Since this difference may be affected by the size and length of branch grafts and the distance between the inflow and outflow sites, CFD seems to be a useful method when pursuing optimal graft design.

Study limitations

This study is limited by the bias inherent to its retrospective single-center design and the small number of patients. The results may also have been influenced by the accumulating experience of surgeons because the study spanned a 13-year period, although the surgical strategy has not changed. CFD was limited to one case with 2 scenarios because of the tremendous cost of CFD outsourcing. However, the CFD simulation was intended to elucidate the influence of the length and diameter of tube grafts when they were connected vertically to the main graft and to the intercostal artery orifice, to exclude the influence of graft kinking. Therefore, the use of the images from other patients will not provide additional information because there is no room for variation in factors other than the size and length. To the best of our knowledge, this is the first study that specifically evaluated the influence of the graft size and length on patency, and that used CFD to evaluate the flow dynamics within the reconstructed intercostal artery. This may open a window for further research in this field.

Conclusion

Eight- and 10-mm grafts seem better than 12-mm grafts, and the graft length should be kept shorter than 25 mm. This may be because the vortical flow generated within the 12-mm graft does not reach the intercostal orifice, and disturbs the helical flow, which may be important for graft patency. CFD may shed light on the issue of optimal intercostal artery reconstruction techniques.

Fundings: None.

Conflict of interest: The authors declare no conflicts of interest in association with the present study.

Data availability: The data underlying this article will be shared on reasonable request to the corresponding author.

Figure legends

Figure 1. Representative images of computed tomography showing graft patency (A) and the method of measuring the graft length (B).

(A) Contrast enhancement of the reconstructed intercostal artery could be traced from the tube graft in continuity (arrowheads). (B) Multiplanar reconstruction was used to measure the graft length.

Figure 2. Operative view and schematic illustration of the reconstruction technique.

(Left) Running suture was performed between the buttress sutures. (Right) Graft-to-graft anastomosis. A clamp was placed on the tube graft to prevent intercostal steal.

Figure 3. Patency according to the size and length of the grafts.

Blue dots: patent, red dots: occluded.

Figure 4. Patency of the grafts shorter than 25 mm used in thoracoabdominal aortic replacement according to the size.

Figure 5. Streamlines generated by computational fluid dynamics.

(A) An original model derived from a patient with a patent 12-mm graft of 15 mm in length. (B) Simulation-1 with a smaller (8-mm) graft of 15 mm in length. (C) Simulation-2 with a longer (30-mm) graft of 12 mm in diameter.

Central image. Patency of the grafts shorter than 25 mm used in thoracoabdominal aortic replacement according to the size.

Video. Streamlines generated by computational fluid dynamics.

Table 1. Patient characteristics.

Extent of replacement	Descending (Extent-C)	11
	Thoracoabdominal	30
	Crawford-I	9
	Crawford-II	3
	Crawford-III	17
	Crawford-IV	1
Number of segments involved		8.0 (Q1 7.0, Q3 9.0)
Thoracoabdominal aortic replacement		9.0 (Q1 7.0, Q3 9.5)
Descending aortic replacement.		8.0 (Q1 7.0, Q3 8.0)
Etiology	Aortic dissection	29
	Degeneration	10
	Infection	2
Circulatory adjunct	Distal aortic perfusion	27
	Deep hypothermia	12

Moderate hypothermia with bidirectional perfusion	2

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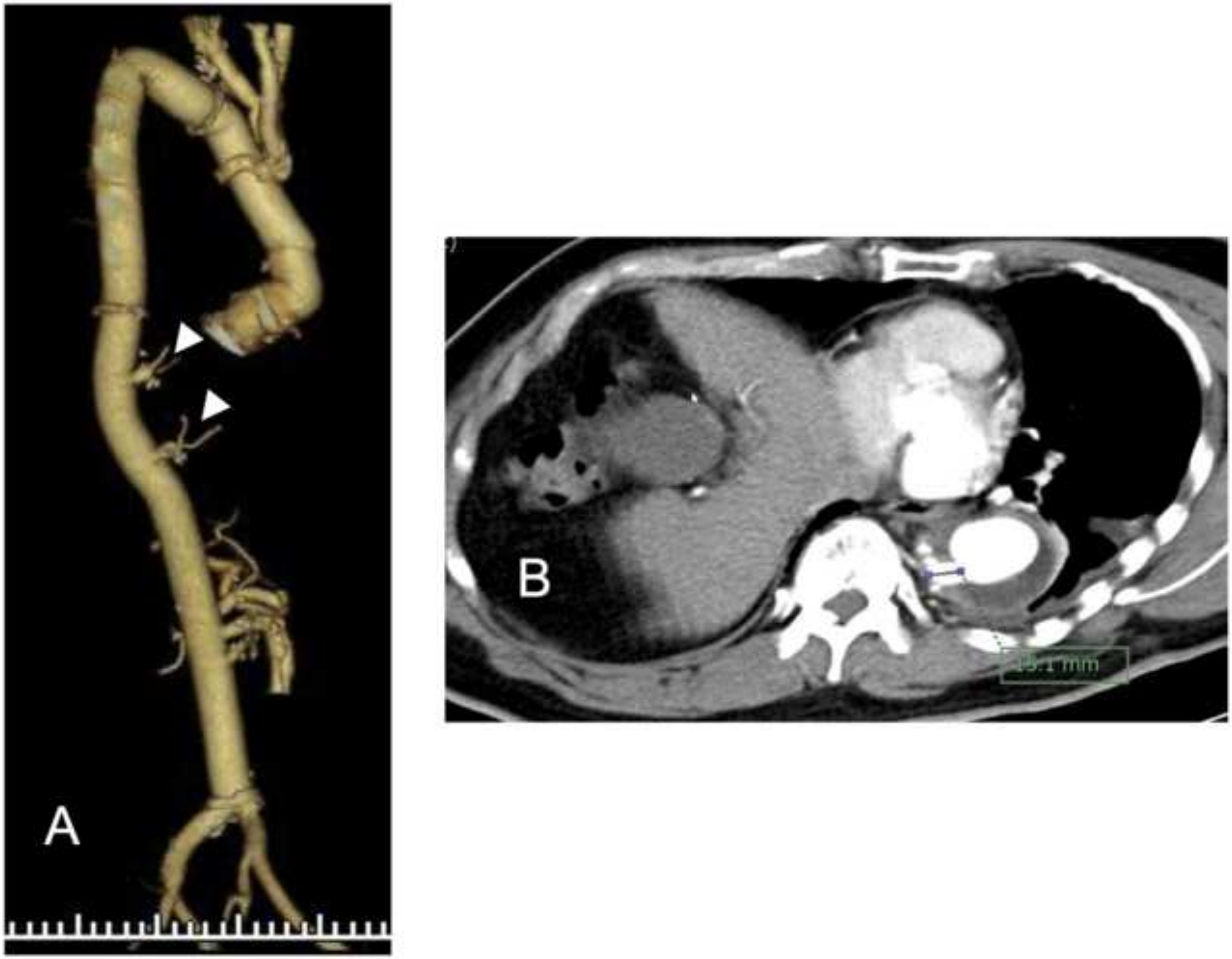

Figure 2

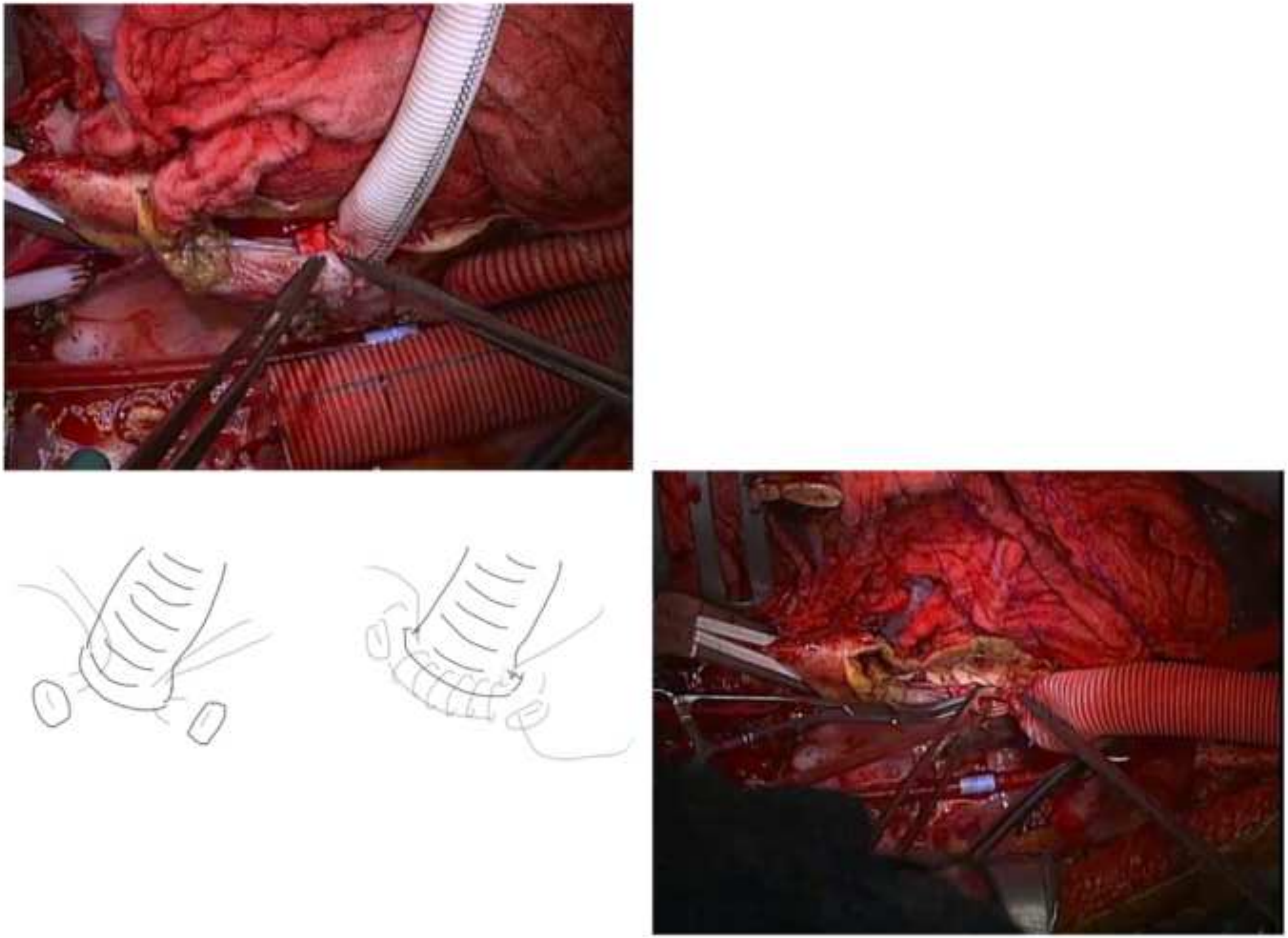

Figure 3

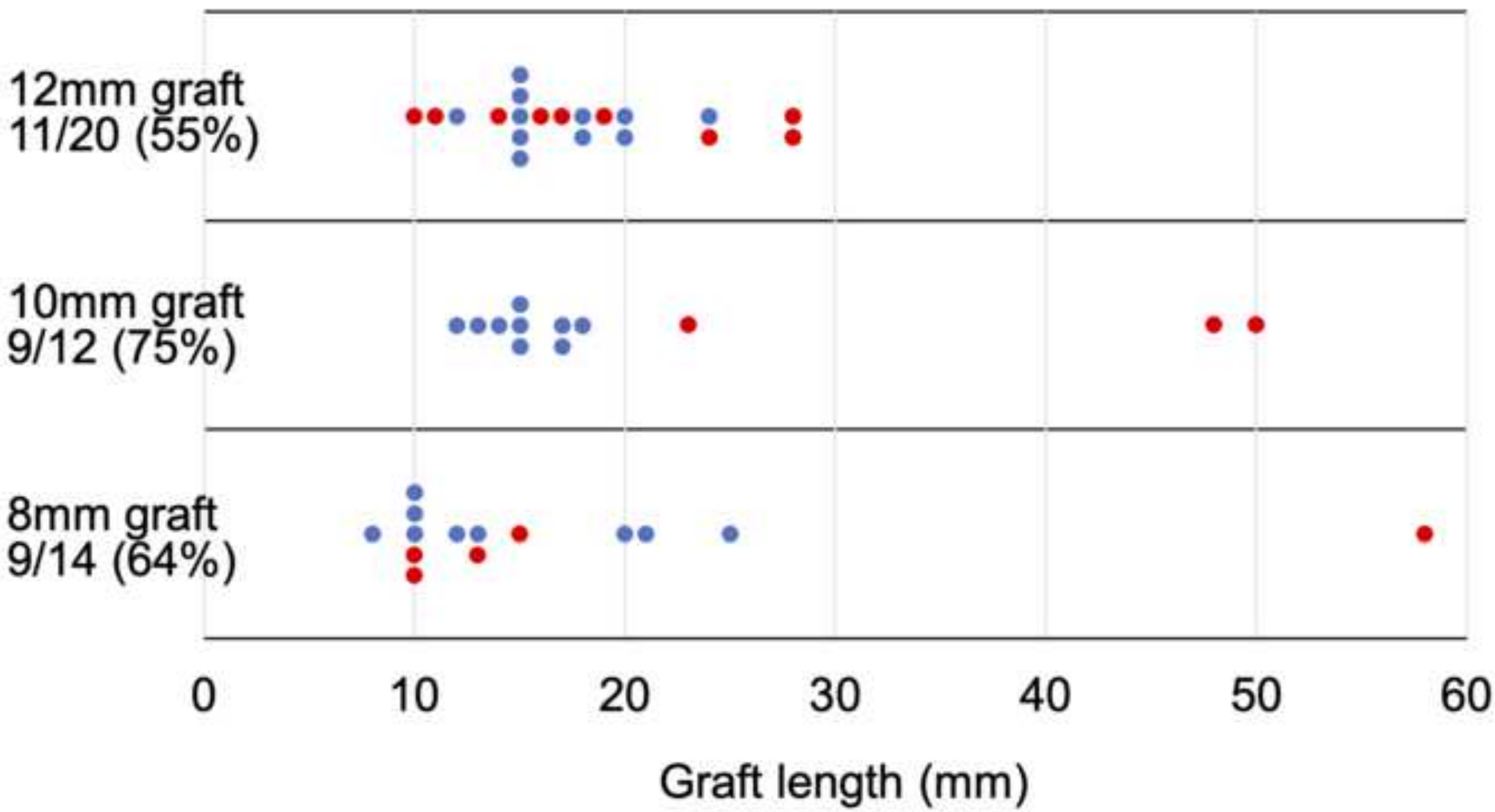
12mm graft
11/20 (55%)
10mm graft
9/12 (75%)
8mm graft
9/14 (64%)
0
10
20
30
40
50
60
Graft length (mm)

Figure 4 Click here to access/download;Figure;Figure 4N.tif

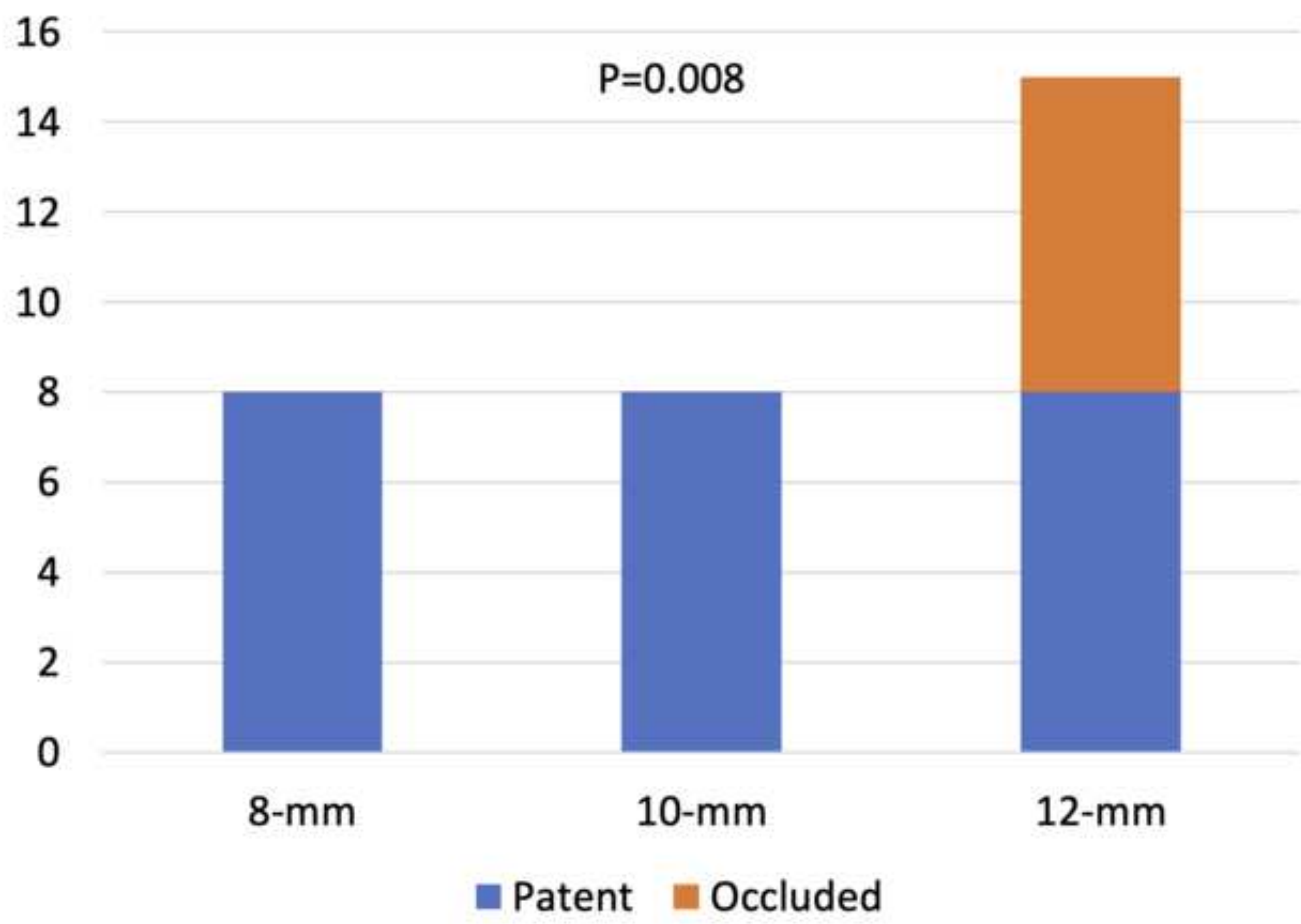

Figure 5

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