Two-Stage Pulsatile Human Placenta Model for Microvascular Anastomosis Training in Neurosurgery

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■ OBJECTIVE: **The development of microsurgical skills is crucial for neurosurgical education. The human placenta is a promising model for practicing vascular anastomosis due to its similarities with brain vessels. We propose a 2-stage model for training in extracranial-to-intracranial anastomosis using the placenta.**

■ METHODS: **Initially, we propose practicing anastomosis in 2 adjacent placentas. Once successful, the procedure advances to a more challenging configuration that employs a 3-dimensionally printed skull with a window simulating a pterional craniotomy. It is positioned an intracranial placenta and an extracranial one, and the latter has a prominent vessel exposed toward the side of the craniotomy. Both placentas have one artery and vein cannulated in the umbilical cord, and we present an artificial placental circulation system for microvascular training that regulates pulsation and hydrodynamic pressure while keeping veins engorged with a pressurized bag. To verify anastomosis patency, we utilize sodium fluorescein and iodine contrast.**

■ RESULTS: **The 2-stage model simulated several aspects of microvascular anastomosis. Our perfusion system allowed for intraoperative adjustments of hydrodynamic pressure and pulsation. Using iodine contrast and fluorescein enabled proper evaluation of anastomosis patency and hydrodynamic features.**

■ CONCLUSIONS: **Training in the laboratory is essential for developing microsurgical skills. We have presented a model for microvascular anastomosis with artificial circulation and postoperative imaging evaluation, which is highly beneficial for enhancing the learning curve in microvascular procedures.**

INTRODUCTION

The first vascular procedures in neurosurgery date back to the 1950s and 1960s, with the works of Welch[1] and Jacobson et al[2] reporting microsurgical embolectomies of occluded middle cerebral arteries. Woringer and Kunlin[3] attempted an extracranial to intracranial anastomosis in 1963, using a saphenous vein graft to connect the common carotid artery to the intracranial carotid artery; however, their patient died. In 1967 Yasargil and et al[4,5] first performed the bypass from the superficial temporal to middle cerebral artery in 2 patients, resulting in favorable outcomes and leading to the development of cerebral revascularization procedures worldwide.

Laboratory training is fundamental for developing and refining microsurgical skills in a controlled environment, as Yasargil emphasized multiple times.[5,6] Nonliving models for training have progressively gained space due to the lack and difficulties of accessing human anatomic specimens or animal models. A promising model is the human placenta, which was first reported for miscellaneous vascular training in 1980, while the first study depicting applicability for neurosurgical training dates back to 1992.[7-9] The average weight of a human placenta is 500–600 gm with a diameter of 17–20 cm. It has both fetal and

Key words
- Anastomosis
- Bypass
- Microsurgery
- Placenta
- Pulsatile

Abbreviations and Acronyms
MCA: Middle cerebral artery
PGY: Postgraduate year

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maternal surfaces. The fetal side is covered by an amniotic membrane that resembles an arachnoid and has a rich vascular network similar in diameter to brain vessels.[10,11] The mean diameter of placental arteries ranges from 5.98 mm near the umbilical cord insertion to 2.62 mm distally. Similarly, vein mean diameters vary from 10.22 mm proximally to 4.20 mm distally.[10] Training with the human placenta has already been shown to improve the learning curve of neurosurgeons and residents in microsurgical vascular procedures.[12,13]

The objective of this study is to outline a cost-effective and reproducible model for microvascular training, using a human placenta, with a particular emphasis on vascular anastomosis.

METHODS

This project received approval from the ethics committee at Mackenzie Evangelical College of Paraná, and informed consent was obtained from obstetric patients for placenta donation after delivery. Cases with positive screenings for infectious diseases or requiring pathologic study of placentas were excluded. Within 12 hours of delivery at the obstetric center, 20 human placentas were collected and washed with running water to clear surface blood clots, and the umbilical cord was sectioned about 10 cm from the placental implantation. The excess amniotic membrane around the placenta was removed, and blood clots were initially removed by palpating the fetal surface toward the umbilical cord. The umbilical vein was cannulated with a 12–14 Fr intermittent urinary catheter, and just 1 of the 2 umbilical arteries was cannulated with an 8- to 12-Fr intermittent urinary catheter, as both arteries usually present an anastomosis close to the umbilical cord implantation. Finally, the umbilical cord was tied while holding the catheters. A period of flushing normal saline was performed for 20 minutes to clear intraluminal blood clots between arterial and venous catheters. Next, 20–30 mL of red pigment was injected into the arterial catheter and capped. The same process was performed with the venous catheter, using methylene blue 1% (**Videos 1**). This allowed for the initial staining of vessels, aiding in the differentiation between arteries and veins. The placentas were then stored frozen at −12°C to −18°C and defrosted by submersion in water for 1 hour before the activity.

Video

Video available at www.sciencedirect.com

To simulate extracranial to intracranial bypass, we propose a 2-stage model. First, we place 2 placentas with fetal surfaces up next to each other, exposing border arteries of different

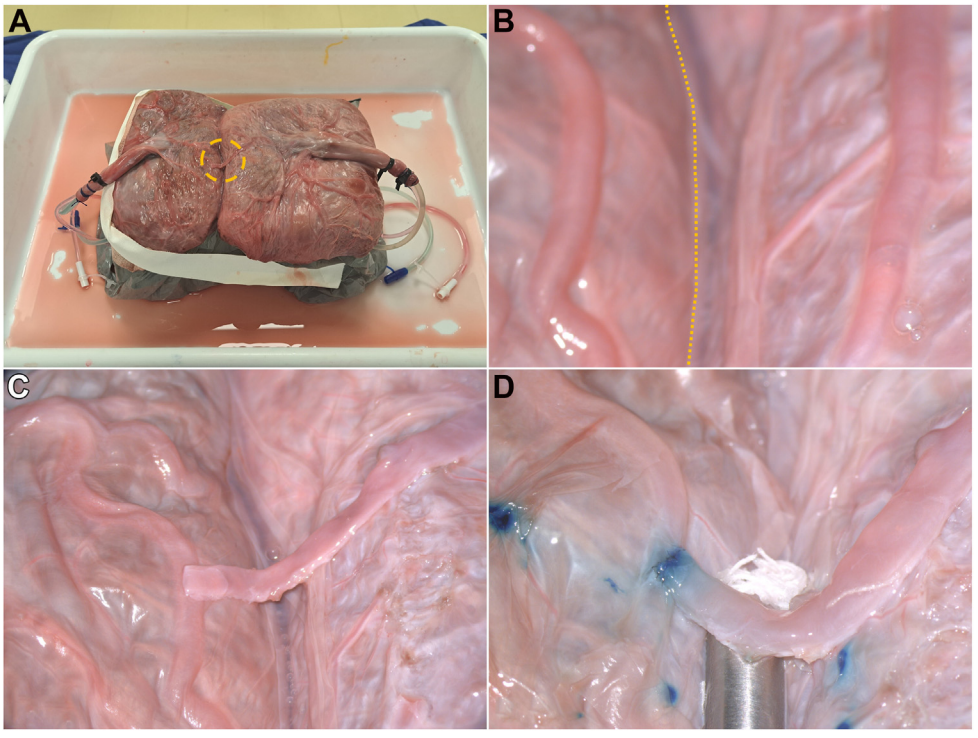

Figure 1. First stage of training module. (**A**) Overview of 2 placentas side by side. (**B**) Microscope image of the boundary between the 2 placentas, highlighted by the dotted line. (**C**) Detached donor artery from 1 placenta and extended to the other one. (**D**) End-to-side anastomosis.

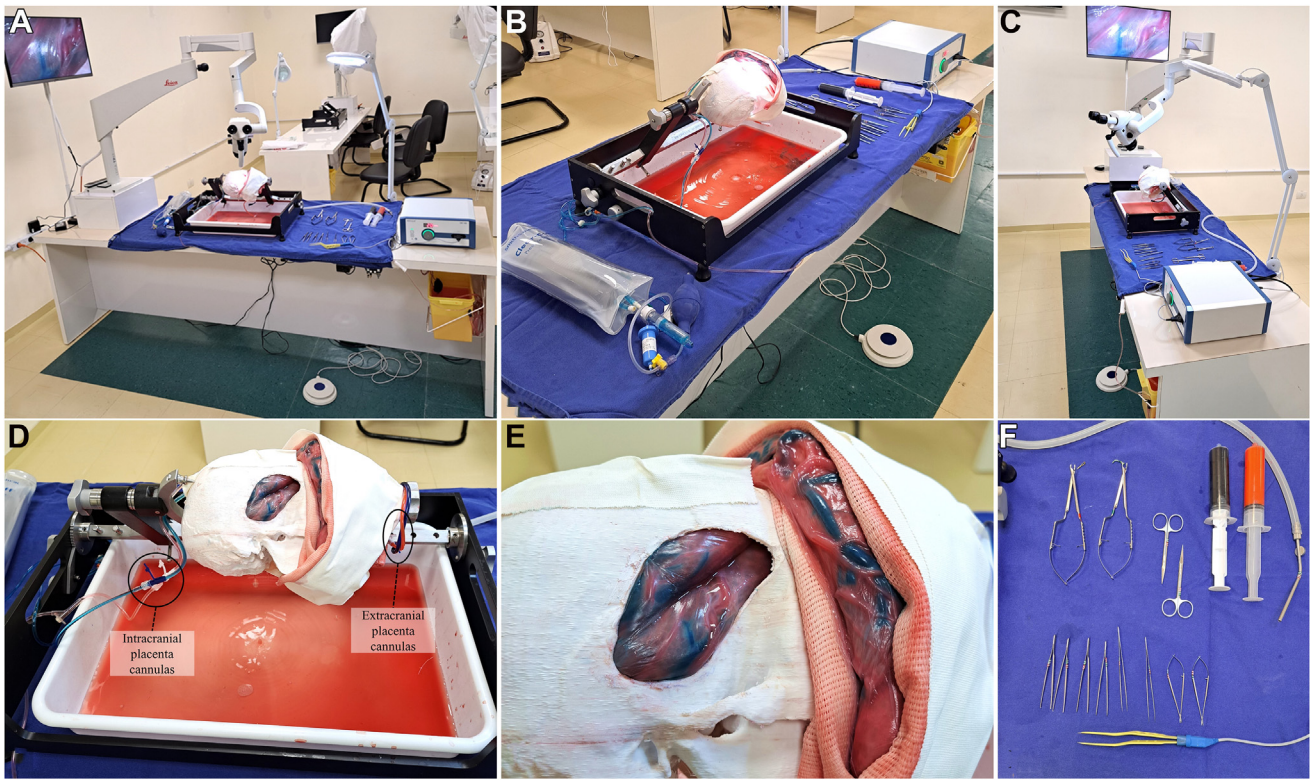

Figure 2. Second stage of training module. (**A**–**C**) The workstation overview illustrates the windscreen washer pump placed under the table. It also demonstrates the venous system's pressurized bag. (**D** and **E**) Configuration of a 3-dimensionally printed skull secured in a 3-point bench headholder, displaying the intracranial and extracranial placentas, both with cannulated artery and vein. (**F**) Overview of basic instruments for microsurgical training.

diameters to simulate a larger donor artery (superficial temporal artery) and a smaller recipient artery (middle cerebral artery [MCA]) (Figure 1). After successfully completing the end-to-side anastomosis in this configuration, the procedure moves on to the next stage.

We created 3-dimensionally printed skulls using polylactic acid (PLA) and added a unilateral window to replicate a pterional craniotomy. The skulls were fixed in place using a 3-point bench headholder, which allowed for adjustable positioning based on the situation. One placenta was folded up and placed inside the skull in a way to simulate sylvian fissure projected in the region of pterional craniotomy; the space left in the skull was filled to keep the placenta in place. The arterial catheter was connected to the pulsatile system described later, and the venous catheter was connected to a pressurized bag filled with 1% methylene blue-colored normal saline. We placed an additional placenta on the outside surface of each skull, with a prominent artery directed toward the side of the craniotomy (Figure 2). The procedure involved dissecting and detaching an arterial segment from the outer placental surface. Next, the artery was brought near the intracranial placental surface to perform the end-to-side anastomosis.

The exercises for microvascular suturing were carried out using regular suture materials like nylon or Prolene with sizes ranging from 9–0 to 10–0, along with a cylindrical needle.

We developed a pulsatile system to simulate an artificial placental circulation (Figure 3). We connected a 24V windscreen washer pump to a potentiometer and an analog timer relay using an adjustable 24V laptop charger as the power source. To avoid overload during extended use, we typically selected an intermediate tension output. This setup allows for adjusting the tension delivered to the pump using a potentiometer. It regulates the hydrodynamic pressure and includes the option to add a manometer to check the pressure in the hydraulic part. The timer relay can be configured to control the on/off time of the pump, allowing for regulation of pulsation. Using a digital timer relay may simplify this adjustment. Additionally, the washer pump should remain slightly submerged in a recipient to function properly. We connected a surgical latex suction tube to the pump outflow and then attached a small piece of sphygmomanometer latex tubing to connect the latex suction to the macrodrops tube, which is then connected to the arterial catheter in the placenta.

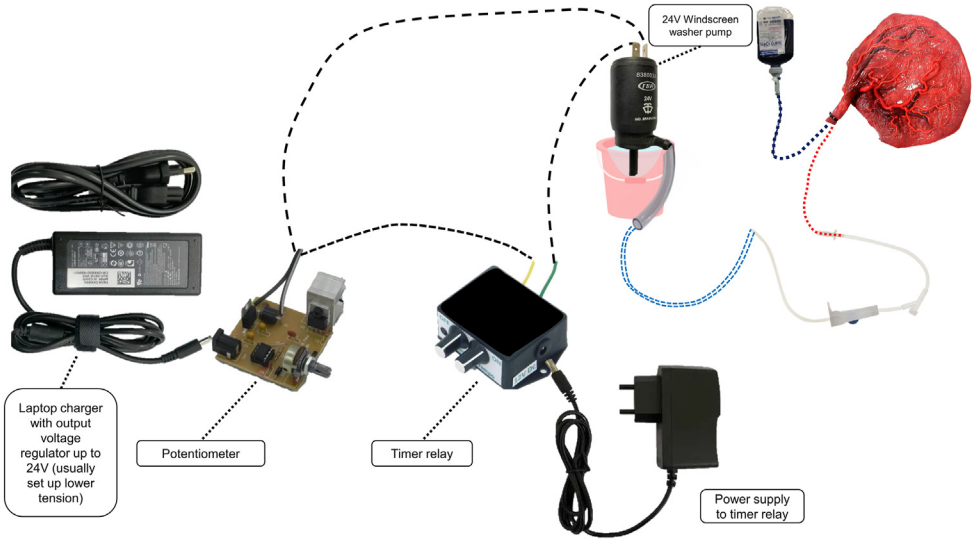

Figure 3. Diagram of the perfusion system with hydrodynamic pressure and pulsation control.

The artificial pulsatile system was preferred to be connected to the intracranial placenta, as the extracranial one would make more evident the normal leakage from the placental maternal surface. In this way, the patency of the anastomosis could be checked by applying pulsatile flow from the intraccranial to extracranial placenta or by using a syringe to apply flow in the opposite direction. However, during the first stage where the placentas are side-by-side, the pulsatile system could be connected to either one as both would be in the same position over the collecting recipient.

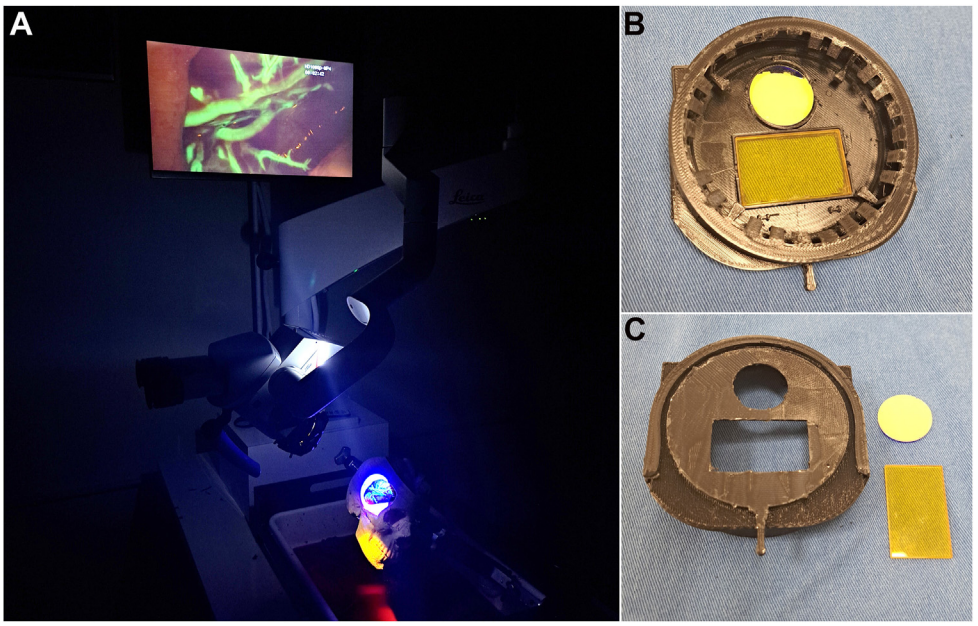

Figure 4. Fluorescence mode employing the filter described by Lovato et al.[15,16] (**A**) Overview of filter adapted to the microscope. (**B**) Inner view. (**C**) External view of the filter and respective lenses.

We employed with some adaptation the device for intraoperative fluorescein-guided surgery previously described by Lovato et al[14,15] to check the patency of the vascular anastomosis. Fluorescein can be administered by injection with a syringe or by adding it to the macrodrops tube while pulsating (**Figure 4**). Another method to check the patency of an anastomosis is to perform a static radiograph a few seconds after the injection of 5–10 mL of iodine contrast or to perform fluoroscopy to obtain a placental angiography. We also tested the patency of anastomosis using a simple red dye in case vessels were clear and translucid.

We tested a 2-stage model in our microsurgical lab with 10 workstations, each equipped with a microscope, microsurgical instruments, aspirator, and our own perfusion system. Medical students, neurosurgery residents, and young and experienced neurosurgeons underwent three 2-day hands-on courses to evaluate the training model's feasibility (**Figure 5**). Placentas were kept frozen until the first day of activities, when they were defrosted. Each item was individually stored and packed in a plastic bag to make defrosting easier. If the same placenta would be used the next day, it was possible to keep it refrigerated at $<10^{o}$C.

We asked course participants to complete a questionnaire created by the authors about training model features (**Table 1**). A 5-point Likert scale was used, with 5 indicating most favorable and 1 indicating most unfavorable evaluation. Significance was assessed using Kruskal-Wallis and Mann-Whitney U tests.

RESULTS

The perfusion system with pressure and pulsation regulation showed good performance during microsurgical procedures (**Videos 1** and **2**). It was possible to adjust the simulated arterial pressure in real time using a potentiometer button. To increase the system's useful life, we chose to use a 24V windscreen washer pump and regulate the power supply from the laptop charger to <24V. Additionally, we used the potentiometer at an intermediate turn most of the time to avoid excessive pressure in circulation. We observed that during perfusion, fluid injected through the arterial cannula also exited the venous cannula, indicating some preservation of arterial-capillary-venous patency. However, fluid leaked from the maternal placental surface, requiring a collection receptacle beneath. We observed that reducing vascular pressure, both arterial and venous, resulted in decreased leakage. To regulate this, we adjusted the potentiometer, maintaining placenta perfusion with the minimum pressure required for realistic simulation. This has made the training process with the perfused model more comfortable. Regarding

Figure 5. (**A** and **B**) Overview of laboratory. (**C**) Example of intracranial placenta inside the 3-dimensionally printed skull. (**D**–**F**) Example of dissection activities.

Table 1. Questionnaire About Subjective Evaluation of the Model by Participants in Hands-on Courses

Face Validity
1. Does it reproduce the surgeon's ergonomic adjustments needed during a surgical procedure?
2. Does it reproduce microvascular dissection procedures?
3. Does it reproduce an end-to-side vascular anastomosis procedure (like superficial temporal artery–middle cerebral artery bypass)?
4. How well did you perform in the general microvascular dissection exercises?
5. How well did you do with the end-to-side vascular anastomosis exercises?
6. Does the inclusion of a pulsating model and engorged veins enhance the realism of the training?
7. How closely does the pulsatile arterial model with engorged veins resemble a real situation?
Content validity
8. Should the training model be a part of neurosurgical resident education?
9. Can the model assist in improving the surgeon's ergonomics during a real procedure?
10. Can it help improve microsurgical techniques?
11. Can it help improve microvascular anastomosis techniques?
12. Do you believe that using a pulsatile model for training results in improved development of microsurgical techniques?
13. Is this model able to replace animal usage in vascular anastomosis training?

the venous system, we can adjust the pressure bag to maintain vein engorgement with minimal leakage.

The placenta and its vessels should be washed and frozen within hours of delivery. It can be stored frozen for up to 2 weeks or refrigerated (<10°C) for up to 24 hours before use. Better results are achieved when dissection exercises are conducted within the first few days after the initial defrost or closer to delivery time. This is because the vessel walls and placental stroma become more fragile progressively.[17]

Vascular anastomosis training focused on superficial temporal artery–middle cerebral artery bypass was achieved with great realism. The 2-stage model allows for the initial practice of microvascular techniques in a simplified scenario with greater spatial freedom and without 3-dimensional depth, facilitating vascular anastomosis construction and inspection. A key point was to avoid getting into the placental parenchyma when dissecting either the donor or recipient vessel, to prevent leakage from inside; this could be achieved by dissecting the plane between the adventitia and a layer covering the parenchyma. It is necessary to ligate or coagulate the small branches arising from placental arteries, whether superficial or deep, to successfully detach the donor artery. This allows for the preparation of a long donor artery to reach the recipient artery and perform the end-to-side anastomosis (**Figure 6**).

To confirm vessel patency, we injected sodium fluorescein into the macrodrops tubing while perfusing the intracranial placenta. Alternatively, it can be injected from the extracranial to intracranial side (**Figure 7**, **Videos 3**). It is advisable to hold a suction tube close to the anastomosis during surgery to check for any expected leakage of fluorescein, which can also help assess the tightness of the suture line. In the first stage of the model,

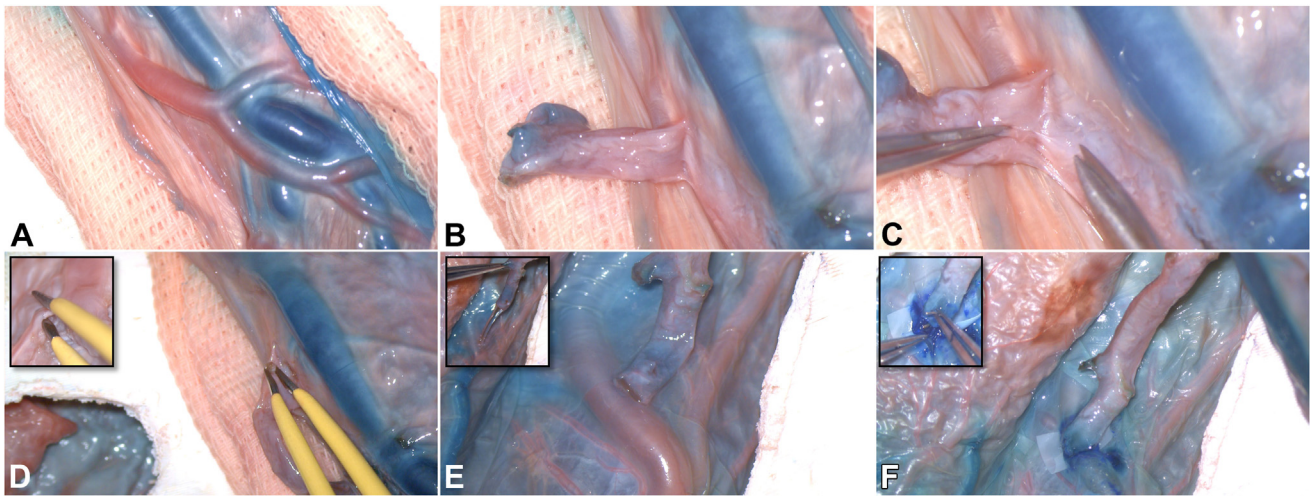

Figure 6. Dissection of a donor artery from extracranial placenta. (**A**) Initial view of the donor artery crossing over a vein. (**B** and **C**) Dissecting donor artery from the placental surface through a plane keeping a membrane covering parenchyma, not violating it. (**D**) Some branches of the placental artery must be ligated or coagulated to progressively dissect and detach a long donor vessel, with detail of coagulation of a larger branch in the inset image. (**E**) Demonstration of enough length of donor artery toward the intracranial recipient artery, presenting detail of flow from the donor vessel in the inset image. (**F**) End-to-side anastomosis and detail of suture in the inset image.

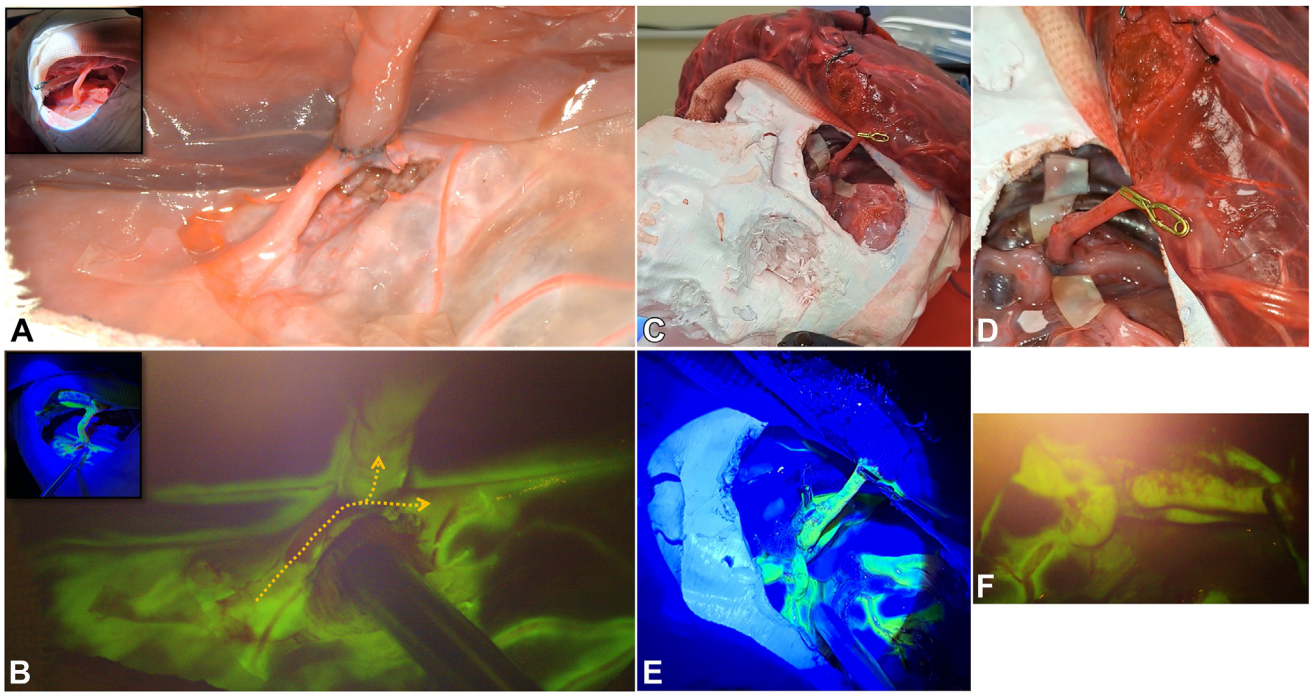

Figure 7. Use of sodium fluorescein to check extracranial to intracranial anastomosis in 2 models. (**A**) White light view of anastomosis, with overview in the inset image. (**B**) Fluorescein confirming patency of anastomosis, with flow from intracranial to extracranial placenta by a microscope view and by naked eye in the inset image. (**C** and **D**) Extracranial to intracranial anastomosis in the other model, demonstrating patency of anastomosis with fluorescein by naked eye (**E**) and by microscope (**F**).

angiography with fluorescein showed the effectiveness of the anastomosis by demonstrating global fluorescence of the vessels in the recipient placenta, which was situated side-by-side with the donor placenta (Figure 8, Videos 4).

Placental angiography using iodine contrast is valuable for objectively evaluating the quality of anastomoses. A static radiograph provided information about patency (Figure 9), but fluoroscopic images bring better evaluation of hydrodynamic (Figure 10, Videos 5). It was possible to use this technique in both stages of the model, but the image quality improved when the placentas were placed side by side because the 3-dimensionally printed skull is slightly radiopaque. In the same way, this technique allows for an indirect evaluation of anastomosis quality by measuring the amount of contrast toward the recipient placenta.

Both techniques using iodine contrast and fluorescein performed well. However, they tended to impregnate the placenta, resulting

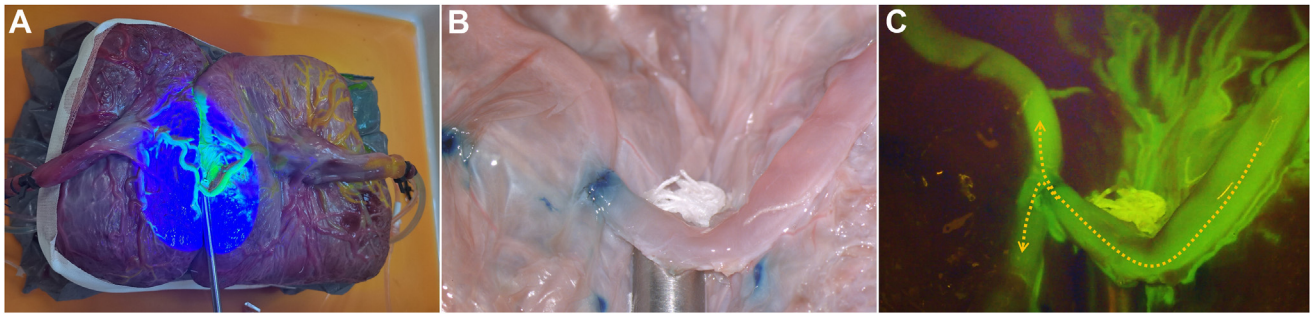

Figure 8. Demonstration of patency of anastomosis between 2 placentas side by side in the first stage of the model. (**A**) Overview of the arrangement of placentas and fluorescence by naked eye. (**B**) Microscope image of anastomosis in white light. (**C**) Microscope image with fluorescence mode/checking anastomosis patency.

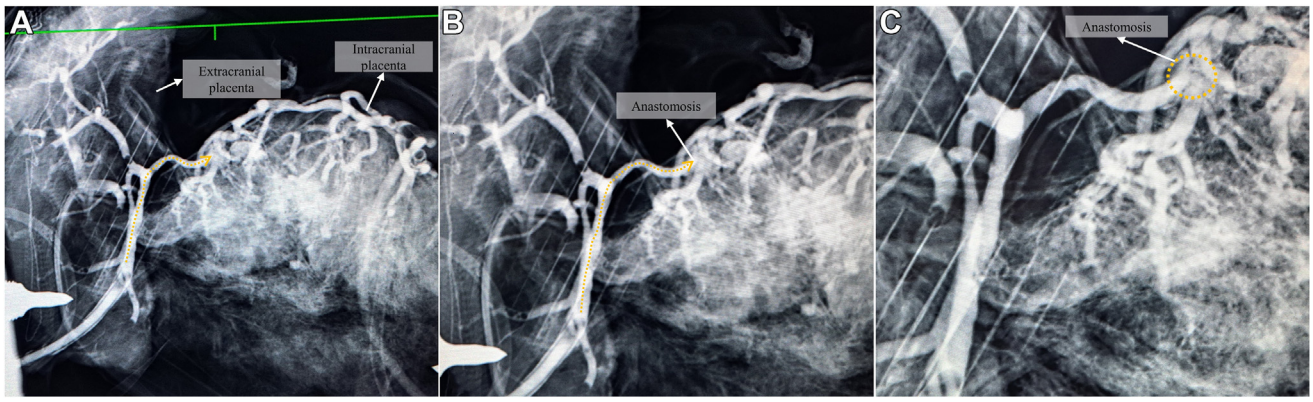

Figure 9. Static radiograph a few seconds after iodine contrast injection from extracranial to intracranial placenta. (**A**) Overview image depicting significant amount of contrast filling the arteries of recipient placenta. (**B** and **C**) Closer images demonstrating patency of anastomosis.

in lower-quality subsequent angiographies. To enable multiple angiographies without placental parenchyma/vessels impregnation, we injected red dye into clear and translucent vessels. This allows for subsequent injections, but it becomes difficult to observe differences between arteries and veins if the latter are not colored (**Videos 6**).

During microvascular training, we discovered that a valuable exercise for improving microsurgical skills is separating a superficial artery from an underlying vein at its intersection, particularly due to the challenges presented by the pulsatile arterial system and the engorged veins caused by the pressurized bag (**Videos 7**). The microvascular suture of vessel walls improves the handling of

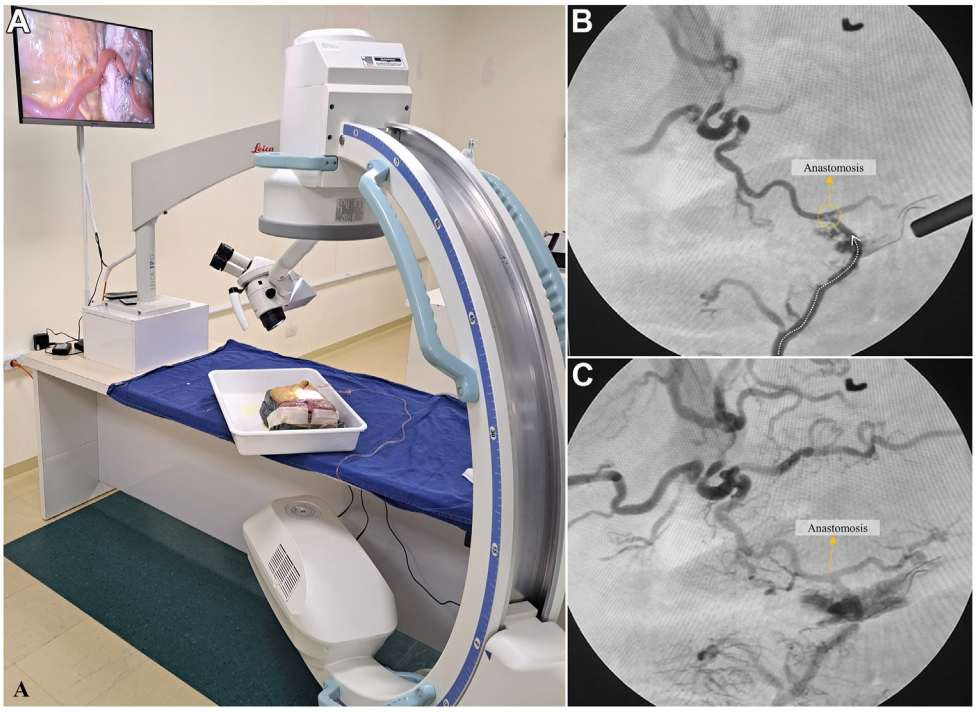

Figure 10. Fluoroscopy images of placentas side by side, checking anastomosis patency and hydrodynamic features. (**A**) Positioning of the equipment. (**B**) Early and (**C**) late (~20s later) view after iodine contrast injection while perfusing placenta with the pulsatile system.

needles, thread, and instruments for successful anastomoses (**Figure 11**).

Thirty-nine participants of the 2-day courses answered the questionnaire, including 8 medical students, 19 neurosurgical residents, and 11 neurosurgeons. The responses related to face validity are shown in **Figure 12**, and those related to content validity are shown in **Figure 13**. Participants were divided into 3 groups based on their level of microsurgical experience: low (medical students, postgraduate year [PGY-1] and PGY-2 residents); intermediate (PGY-3 to 5); and attending. **Tables 2** and **3** show that on average all participants gave an overall score of 4 or higher. The groups did not differ significantly in their responses.

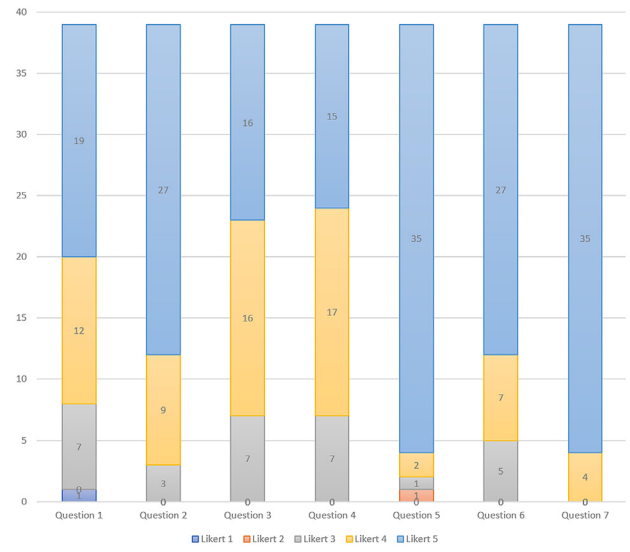

Figure 12. Distribution of responses to the questions 1-7 related to face validity considering the Likert-scale.

DISCUSSION

Different studies have already reported the placenta model as a simulator for training of Sylvian fissure dissection and aneurysm clipping[16,18]; microsurgical embolectomy[19]; vascular anastomosis[10,20,21]; and tumor resection.[22] Perfusion of placenta simulator achieves a more realistic training, keeping the vessels filled and simulating intraoperative bleeding that demands adequate control.[16,18]

Laboratory microsurgical training is necessary to refine skills for the operating room. Rat models are the gold standard for microvascular training due to their versatility, realism, and ability to check anastomosis patency in a live environment.[23-25] Over the past few years, the human placenta has become a promising model that has undergone progressive improvements. On the basis of initial reports, it only demonstrated face and content validity[26]; however, more recent studies reported also construct and predictive validities for microvascular training.[13,20,27] The human placenta model is a great alternative to live models,

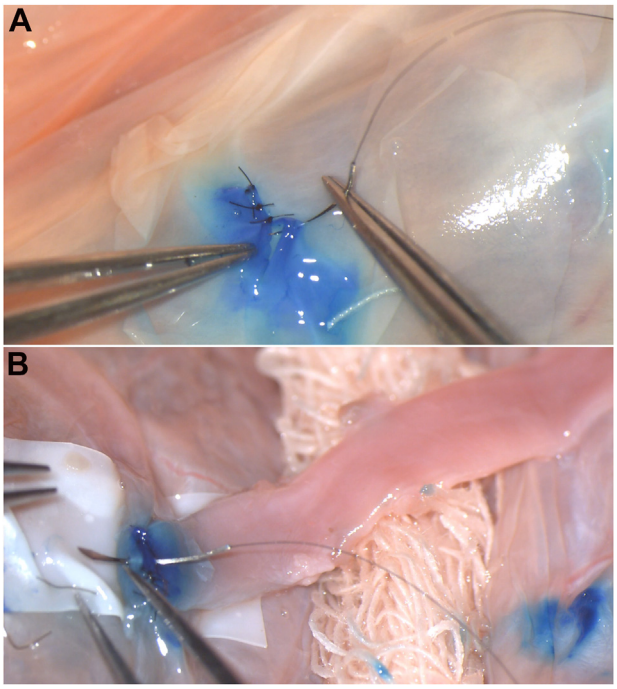

Figure 11. (**A**) Microvascular suture of incised arterial wall. (**B**) Microvascular suture of an end-to-side anastomosis.

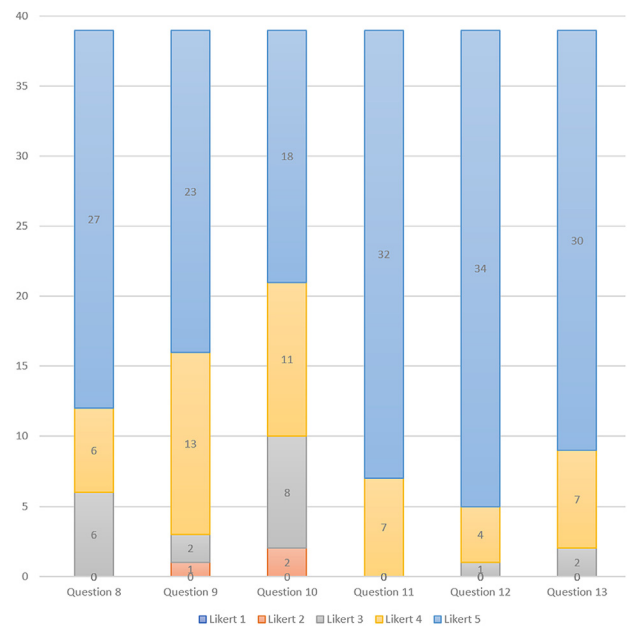

Figure 13. Distribution of responses to the questions 8-13 related to content validity considering the Likert-scale.

Table 2. Responses to Questions 1–7 About the Face Validity of the Model Comparing Low-Experience, Intermediate-Experience, and Attending Groups

		Q1	Q2	Q3	Q4	Q5	Q6	Q7
	Number	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Medical student + PGY 1–2	15	4.23 ± 1.1	4.67 ± 0.62	4.67 ± 0.62	4.1 ± 0.7	3.6 ± 1.12	4.67 ± 0.49	4.2 ± 0.68
PGY 3–5	12	4.25 ± 0.87	4.33 ± 0.65	4.67 ± 0.65	4 ± 0.74	4.17 ± 0.83	4.75 ± 0.45	4.42 ± 0.67
Neurosurgeon	12	4.17 ± 0.83	4.42 ± 0.91	4.5 ± 0.67	4.33 ± 0.89	4.42 ± 0.79	5 ± 0	4.25 ± 0.75
Total	39	4.23 ± 0.93	4.49 ± 0.72	4.62 ± 0.63	4.13 ± 0.77	4.03 ± 0.99	4.79 ± 0.41	4.28 ± 0.69

PGY, postgraduate year (in Brazil, neurosurgery residency is 5 years following medical school); Q, question.

aligning with the 3Rs principles of Russell and Burch (*replacement, reduction, refinement*).[28] Microsurgical training in the placenta produces better simulations of Sylvian fissure and aneurysm dissection than the cadaveric model but lacks neuroanatomic fidelity. This highlights the potential superiority of using human placenta for microsurgical skills training compared with cadaveric models.[13] Human placenta is a widely available material for medical training, but it requires ethical evaluation and mother consent, as well as access to an obstetric center, which can be difficult in some locations. Compared with animal or cadaver models, accessing the placenta is easier, cheaper, and raises fewer ethical concerns.

We described a low-cost perfusion system that is easy to set up. It is pulsatile and has pressure control, allowing for real-time adjustment of the desired simulated arterial condition. This brings more realism to the procedure. An important practical point is to adjust the pressure to the lowest necessary level to maintain perfusion, which reduces expected leakage from the placental maternal surface. Most authors describe perfusion of the placenta either with a syringe or through gravitational drip using a normal saline bottle. We only found 1 previous description of a pulsatile system, but it did not address venous system filling like we did.[18] We provided a detailed guide on setting up our perfusion system, complete with a building diagram, to ensure easy reproducibility (**Figure 3**).

Our model employing 3-dimensionally printed skull with intra and extracranial placentas, associated with our perfusion system and microsurgical instruments, bipolar coagulator, suction, and aneurysm clips allowed to simulate in an ex vivo model several nuances of a real intraoperative scenario. The initial training configuration uses 2 placentas side by side to introduce the procedure's necessary skills in an easier scenario without 3-dimensional depth. This improves the learning curve to perform anastomosis in the model using tridimensional perspective employing the skull.

We mentioned the use of 20 placentas in our laboratory courses. With 10 training stations, each station uses 2 placentas for the first stage and then reuses them for the second stage. The placental arterial network consists of terminal branches. If arterial damage occurs in the first stage, this branch can be ligated to prevent leakage in the second phase. However, training exercises can be conducted with a smaller number of specimens, in locations with an accessible and concordant obstetric center.

We pointed the possibility to check anastomosis patency employing fluorescein, iodine contrast, and simple red dye.

Table 3. Responses to Questions 8–13 About the Content Validity of the Model Comparing Low-Experience, Intermediate-Experience, and Attending Groups

		Q8	Q9	Q10	Q11	Q12	Q13
	Number	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Medical student + PGY 1–2	15	4.87 ± 0.35	4.67 ± 0.62	4.8 ± 0.41	4.8 ± 0.41	4.73 ± 0.46	4.53 ± 0.74
PGY 3–5	12	5 ± 0	4.5 ± 0.8	5 ± 0	4.83 ± 0.58	4.67 ± 0.65	4.5 ± 0.8
Neurosurgeon	12	5 ± 0	4.58 ± 0.79	5 ± 0	4.92 ± 0.29	4.75 ± 0.62	4.59 ± 0.79
Total	39	4.95 ± 0.22	4.59 ± 0.72	4.92 ± 0.27	4.85 ± 0.43	4.72 ± 0.56	4.54 ± 0.76

PGY, postgraduate year (in Brazil, neurosurgery residency is 5 years following medical school); Q, question.

Objective evaluation of anastomosis quality is important for learning curve improvement. This was suggested by a previous study using indocyanine green.[16] However, we have not found any reports in the literature regarding the use of fluorescein or iodine contrast for the objective of checking anastomosis patency. The latter has previously only been associated with placenta as a neurointerventional model.[29,30] Postoperative imaging can evaluate suture tightness, stenosis, and patency of flow to recipient artery in both directions and indirectly assess contrast reaching arterial network of recipient placenta, highlighting hydrodynamic feature.

We only found 1 previous report with a similar configuration for our model of intracranial and extracranial placentas[21]; however, we made several adjustments in the positioning of the placentas, skull, and headholder. This report[21] mentions the limitation of inadequate assessment of anastomosis patency, which we have overcome with our perfusion system to create a live placenta model.

The hands-on courses' participants gave the training model high ratings, highlighting it as a promising model for neurosurgical education. Specifically, 37 of 39 participants rated model 4 or 5 in question 8 regarding the model's suitability for inclusion in residents' routine training. Participants evaluated the model as an adequate simulator for improving microsurgical skills.

The main limitation of our model is the missing of neuroanatomic fidelity. In this way this model should be complementary to neuroanatomic study, for practicing in the placenta model microsurgical skills.[12,13]

CONCLUSION

Microsurgical training in laboratory is an essential domain of the neurosurgical education, to practice and develop microsurgical skills in a controlled environment. We present a low-cost and easy-to-set-up model for microsurgical training of vascular anastomosis, which combines isolated ideas from previous reports into a realistic and dynamic configuration. We have detailed methods for checking the patency of vascular anastomosis and studying its hydrodynamics. Further studies are required to assess the external validity and reproducibility of this model, to make it easily accessible to neurosurgery residents and neurosurgeons to help them improve their learning curve of microsurgical skills.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Guilherme H.W. Ceccato: Conceptualization, Methodology, Software, Investigation, Data curation, Writing — original draft, Visualization. **Rodrigo S. Foltran:** Investigation, Data curation, Writing — original draft, Visualization. **Kauê Franke:** Investigation, Data curation, Writing — original draft, Visualization. **Renan M. Lovato:** Investigation, Data curation, Writing — original draft, Visualization. **Arthur A. Nicolato:** Investigation, Data curation, Writing — original draft, Visualization. **Sebastiao N.S. Gusmão:** Investigation, Data curation, Writing — original draft, Visualization, Writing — review & editing. **Marcelo M.R. Oliveira:** Investigation, Data curation, Writing — original draft, Visualization, Writing — review & editing. **Luis A.B. Borba:** Conceptualization, Methodology, Supervision, Project administration, Writing — review & editing.

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SUPPLEMENTARY DATA

Supplementary Table 1. Mean and standard deviation of responses to questions 1–7 about the model's face validity, compared across experience groups

		Q1	Q2	Q3	Q4	Q5	Q6	Q7
	Number	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Medical student	8	4.75 ± 0.46	4.88 ± 0.35	4.88 ± 0.35	4 ± 0.76	3.38 ± 1.19	4.88 ± 0.35	4.13 ± 0.83
PGY 1–2	7	3.71 ± 1.38	4.43 ± 0.79	4.43 ± 0.79	4.14 ± 0.69	3.86 ± 1.07	4.43 ± 0.53	4.23 ± 0.49
PGY 3	6	4.17 ± 0.98	4.5 ± 0.55	5 ± 0	4.33 ± 0.82	4.5 ± 0.55	4.83 ± 0.41	4.67 ± 0.52
PGY 4–5	6	4.33 ± 0.82	4.17 ± 0.75	4.33 ±0.82	3.67 ± 0.52	3.83 ± 0.40	4.67 ±0.52	4.17 ± 0.75
Neurosurgeon 1–3 years	7	4 ± 1	4.57 ±1.11	4.57 ± 0.79	4.23 ± 0.95	4.43 ± 0.79	5 ± 0	4.72 ± 0.90
Neurosurgeon 6–15 years	5	4.4 ± 0.55	4.6 ± 0.55	4.4 ±0.55	4.4 ± 0.89	4.4 ± 0.89	5 ± 0	4.4 ± 0.55

PGY, postgraduate year (in Brazil, neurosurgery residency is 5 years following medical school); Q, question.

Supplementary Table 2. Responses to questions 8–13 regarding content validity of the model are presented as mean ± standard deviation, with comparisons made among different experience groups

		Q8	Q9	Q10	Q11	Q12	Q13
	Number	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Medical student	8	5 ± 0	4.88 ± 0.35	5 ± 0	5 ± 0	4.87 ± 0.35	4.5 ± 0.93
PGY 1–2	7	4.71 ± 0.49	4.43 ± 0.79	4.57 ± 0.53	4.57 ± 0.53	4.57 ± 0.53	4.57 ± 0.53
PGY 3	6	5 ± 0	4.83 ± 0.41	5 ± 0	5 ± 0	4.83 ± 0.41	4.5 ± 0.84
PGY 4–5	6	5 ± 0	4.17 ± 0.99	5 ± 0	4.67 ± 0.82	4.5 ± 0.84	4.5 ± 0.84
Neurosurgeon 1–3 years	7	5 ± 0	4.43 ± 0.98	5 ± 0	5 ± 0	4.71 ± 0.76	4.43 ± 0.98
Neurosurgeon 6–15 years	5	5 ± 0	4.8 ± 0.45	5 ± 0	4.8 ± 0.45	4.8 ± 0.45	4.8 ± 0.45

PGY, postgraduate year (in Brazil neurosurgery residency is 5 years following medical school); Q, question; SD, standard deviation.