# Advancing Neurosurgical Skills: A Comparative Study of Training Models for Intra-Extracranial Cerebral Bypass

*Thania de Oca-Mora[1], Carlos Castillo-Rangel[1], Gerardo Marín[2], Cristofer Zarate-Calderon[3], Jonathan Samuel Zúñiga-Cordova[4], Daniel Oswaldo Davila-Rodriguez[1], Helen Ruvalcaba-Guerrero[5], Valeria Forlizzi[6], Matias Baldoncini[7,8]*

■ BACKGROUND: **Training in anastomosis is fundamental in neurosurgery due to the precision and dexterity required. Biological models, although realistic, present limitations such as availability, ethical concerns, and the risk of biological contamination. Synthetic models, on the other hand, offer durability and standardized conditions, although they sometimes lack anatomical realism. This study aims to evaluate and compare the efficiency of anastomosis training models in the intra-extracranial cerebral bypass procedure, identifying those characteristics that enhance optimal microsurgical skill development and participant experience.**

■ METHODS: **A neurosurgery workshop was held from March 2024 to June 2024 with 5 vascular techniques and the participation of 22 surgeons. The models tested were the human placenta, the Wistar rat, the chicken wing artery, the nasogastric feeding tube, and the UpSurgeOn Mycro simulator. The scales used to measure these models were the Main Characteristics Score and the Evaluation Score. These scores allowed us to measure, qualitatively and quantitatively, durability, anatomical similarity, variety of simulation scenarios, risk of biological contamination, ethical considerations and disadvantages with specific infrastructure.**

■ RESULTS: **The human placenta model, Wistar rat model, and UpSurgeOn model were identified as the most effective for training. The human placenta and Wistar rat models were highly regarded for anatomical realism, while the UpSurgeOn model excelled in durability and advanced simulation scenarios. Ethical and cost implications were also considered.**

■ CONCLUSIONS: **The study identifies the human placenta and UpSurgeOn models as optimal for training in intra-extracranial bypass procedures, emphasizing the need for diverse and effective training models in neurosurgery.**

## INTRODUCTION

The intra-extracranial cerebral bypass is a sophisticated surgical procedure pioneered by Dr. Gazi Yasargil in 1967. This procedure is specifically developed to enhance or restore blood circulation in brain regions impacted by obstructions or abnormalities in the blood vessels.[1-3] It provides a vital solution in cases when traditional treatments are ineffective. It is primarily employed in instances of intricate cerebrovascular

**Key words**
- Intra-extracranial cerebral bypass
- Microsurgical competence
- Simulation in neurosurgery
- Surgical training models
- Vascular disorders

**Abbreviations and Acronyms**
**CIOMS**: Council for International Organizations of Medical Sciences
**ES**: Evaluation Score
**ICLAS**: International Council for Laboratory Animal Science
**LaNeMic**: Microsurgical Neuroanatomy Laboratory
**MCS**: Main Characteristics Score
**SD**: Standard deviation

*From the [1]Department of Neurosurgery, Hospital Regional "1° de Octubre", Institute of Social Security and Services for State Workers (ISSSTE), Mexico City, Mexico; [2]Neural Dynamics and Modulation Lab, Cleveland Clinic, Cleveland, Ohio USA; [3]Department of Biophysics, Brain Research Institute, Universidad Veracruzana, Xalapa, Veracruz, Mexico; [4]Department of Vascular Neurosurgery, National Medical Center "20 de Noviembre", Institute of Social Security and Services for State Workers (ISSSTE), Mexico City, Mexico; [5]Universidad Anáhuac Veracruz Campus Xalapa, Xalapa, Veracruz, Mexico; [6]Microsurgical Neuroanatomy Laboratory, Second Chair of Anatomy, University of Buenos Aires, Buenos Aires, Argentina; [7]Neurosurgery. Petrona V. de Cordero Hospital, San Fernando, Buenos Aires, Argentina; and [8]Microsurgical Neuroanatomy Laboratory, Second Chair of Anatomy, University of Buenos Aires, Buenos Aires, Argentina*

*To whom correspondence should be addressed: Gerardo Marín, M.D., Ph.D.
[E-mail: marinmg@ccf.org]*

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disorders, such as large aneurysms, tumors that impact the cerebral blood vessels, and essential illnesses like severe arteriosclerotic stenosis, strokes, or transient ischemic episodes, and Moyamoya disease.[1,4] The process entails establishing a connection between an external blood vessel, typically the superficial temporal artery, and the middle cerebral artery. This bypasses parts of the brain that are diseased or injured, enabling efficient and enduring reperfusion.[5]

The incidence of cerebrovascular diseases necessitating bypass operations has risen in recent decades due to advancements in diagnostic detection and population aging. An extensive investigation has shown a notable rise in cerebrovascular disease incidents, particularly among young adults, emphasizing the growing necessity for efficacious therapies such as bypass surgery.[6,7]

Proficiency in cerebrovascular surgery necessitates a distinct combination of skills and expertise, including a comprehensive understanding of the anatomical intricacies of the cerebral vascular system, adeptness in bimanual surgical techniques, astute problem-solving abilities, and the ability to make informed decisions. Since the opportunities to perform bypass procedures in cerebral pathology are limited, training on a simulator that closely mimics cerebral vessels would enhance microsurgical dexterity.[8] These simulators enable surgeons to cultivate and refine their expertise in a regulated setting, which is essential prior to doing actual treatments. Furthermore, ongoing training is crucial for upholding superior levels of care and enhancing clinical results for patients, particularly as the applications for cerebral bypass surgery increase and the procedure advances.[9,10]

Hence, implementing innovative training models and simulations is of the utmost importance in surgeons' training. This enables them to practice and refine intricate skills safely and efficiently, enhancing surgeons' proficiency, improving patient safety, and improving surgical results.[9]

This study aims to evaluate and compare the efficiency of various training models for anastomosis, both biological and synthetic, in the intra-extracranial cerebral bypass procedure. Using a quantitative and qualitative approach, the study aims to identify the characteristics that enhance the development of microsurgical skills and participant experience, considering both beneficial and limiting aspects during practice. Through the implementation and evaluation of 4 microvascular anastomosis models (Human Placenta, Wistar Rat, Chicken Wing Artery, and Synthetic Tube) and 1 intra-extracranial cerebral bypass model (UpSurgeOn Mycro), this study aims to establish a reference framework for the training of neurosurgeons in cerebral bypass techniques.

## METHODS

A neurosurgery workshop consisting of 5 vascular techniques[11] (anastomoses) for practice was conducted to improve procedures for intra-extracranial cerebral bypass from March 2024 to June 2024. A total of 22 members participated in this study, including neurosurgeons, neurosurgery residents, and vascular or endovascular fellows, 21 of whom were of Latin American origin and 1 from the Middle East. Each model required end-to-end, end-to-side, and side-to-side anastomoses. All participants were supervised and validated by an expert in vascular neurosurgery from the Microsurgical Neuroanatomy Laboratory (LaNeMic).

As a first step, a quantitative evaluation was conducted for each of these training models for bypass procedures, quantifying their main characteristics. These were determined based on qualitative practice concepts and grouped as positive and limiting factors according to the following parameters, marking 1 if the model was considered to have this characteristic or 0 otherwise:

### Positive Characteristics

*Durability for subsequent training*: Used to measure the model's reusability.

*Similarity to cerebral arteries*: Parameter based on anatomy regarding the similarity of relatively small vascularity (2.5—0.5 mm).

*Variety of simulation scenarios for different bypass techniques*: Measurement used for the heterogeneity of vessels, texture, and varied anatomical aspects.

### Limiting Characteristics

*Increased risk of biological contamination*: Focused on determining the possible biological risks for the practitioner and the test model.

*Requires approval from ethics committees*: Parameter used to determine the ethical aspects of using materials for each model.

*Requires specific infrastructure for model handling*: Established to determine the complexity before practices, focusing on presurgical setup and preparation.

Each parameter was scored individually, with 22 being the highest value and 0 being the lowest. In the end, each of these scores was added for each model, both in the positive and limiting factors (with a maximum score of 66 and a minimum of 0), and this value was called the Main Characteristics Score (MCS).

Additionally, another qualitative parameter was measured, considering the advantages and disadvantages of each model, taking into account both the established parameters and the participants' experience during the procedure. These factors could include, for example, anatomical similarity (vascularity or texture), price, ease of acquisition, etc.

Finally, participants were asked to specify their model of choice and provide a quantitative evaluation on a scale from 1 to 10, where 1 indicates an inadequate model, and 10 denotes a highly suitable model based on the established parameters and the experience gained upon completion of the training. The obtained value was determined as an *Evaluation Score* (ES).

The study was carried out at the LaNeMic, belonging to the second chair of anatomy of the University of Buenos Aires, and in the Laboratory of the Central Bioterium of the Faculty of Pharmacy and Biochemistry of the same university, where rodent management was managed. The Faculty of Pharmacy and Biochemistry Ethics Committee of the Institute of Medical Sciences approved the experimental work. The care standards described by the "International Guiding Principles for Biomedical Research Involving Animals" written by the Council for International Organizations of

Medical Sciences (CIOMS) and by the International Council for Laboratory Animal Science (ICLAS), Geneva 2012, were followed.

We used 3 biological and 2 synthetic training models. The biological models included a human placenta, a Wistar strain rat, and a chicken wing. The synthetic models included an UpSurgeOn Mycro training system and a nasogastric feeding probe.

### Training Instruments

We used a Newton training surgical microscope, the MEC XXI series 2000 model, with a fixed and mobile 200-mm lens and a Mizuho micro-Doppler. In addition, during the training sessions, the surgical instruments available were straight and curved watchmaker's tweezers, vascular dilators, microsurgery needle holders, dissection scissors, adventitia scissors, Metzenbaum scissors, microclips, clip holders, handle and scalpel blade N-11, insulin syringes, and 9−0 monofilament nylon with atraumatic needle 1/4 or 3/8 of a circle, conical tip, and flattened body.

### Preparation of Models and Description of Surgical Procedures

***Human Placenta.*** For this model, a human placenta was necessary. To prepare the human placentas, we removed the choriamniotic membrane and blood residues. Blood vessels were cannulated with a No. 6 Nelaton probe fixed at the proximal end of the umbilical cord. A red stain was applied to arteries and a blue stain to veins. After preparation, the placentas were refrigerated for 6−12 hours. During the training session, a vessel was chosen for dissection; the placental *stroma* was released with the watchmaker's tweezers and microscissors. End-to-end, end-to-side, and side-to-side anastomoses were performed, placing 2 clips to isolate the *bypass* site at a distance of 1.5−2 cm for each procedure.[12] Finally, the clips were removed, and permeability was verified with an insulin syringe filled with saline solution (Figure 1).

***Rodent Model (Wistar Strain Rat).*** A 300-g Wistar strain rat was used. The rat was fixed to a surgical camp and anesthetized peritoneally with ketamine at 30 mg/kg and atropine at 1 mg/kg. The procedure started with a linear skin incision from the mandibular symphysis to the sternal manubrium, followed by dissection of the platysma and the submaxillary glands laterally. After identifying the carotid triangle, the omohyoid muscle was incised to expose the carotid sheath, reaching the common carotid artery, the vagus nerve, and the internal jugular vein. Distal and proximal clamps were made with 9-mm miniclips. The anastomoses were performed with a transverse arteriotomy, washing the arterial lumen with heparinized saline solution. Simple separate points were made with a 9−0 monofilament nylon suture until symmetrical confrontation was achieved.[13] After removing both miniclips, permeability was verified with a micro-Doppler (Figure 2).

***Chicken Wing Artery.*** In this practice, a chicken wing was previously washed with a saline solution to remove blood residues. After dissecting the skin from the shoulder to the tip on the ventral surface, surgeons were able to identify the brachial and radial arteries. Under the Newton microscope, trainees had to perform an end-to-end anastomosis on the radial artery and side-to-side and end-to-side anastomoses on the brachial artery; participants used 9−0 nylon.[13] Permeability was verified by an insulin syringe filled with saline solution (Figure 3).

***Synthetic Tube Model.*** Nasogastric feeding probes for premature infants of 2 mm diameter by 45 cm were used. The catheter was placed in the field and fixed at the ends with adhesive tape. With the support of the previously mentioned microscope, an end-to-end anastomosis was performed with 9−0 nylon using the previously described anastomosis techniques[13] (Figure 4). Permeability was verified using continuous saline irrigation.

***UpSurgeOn.*** The UpSurgeOn Mycro training system works for anastomosis and micro sutures designed for the training of complex neurosurgical procedures such as cerebral bypass. This model combines anatomical realism with technology for training, developing, and refining neurosurgical skills. It has been reusable and has been manufactured using 3D technology using silicones and resins (Figure 5). The model includes disposable vessels with a blood flow simulation system, a leak-proof system, and a Skill Series application that provides setup guides and a library of educational videos.

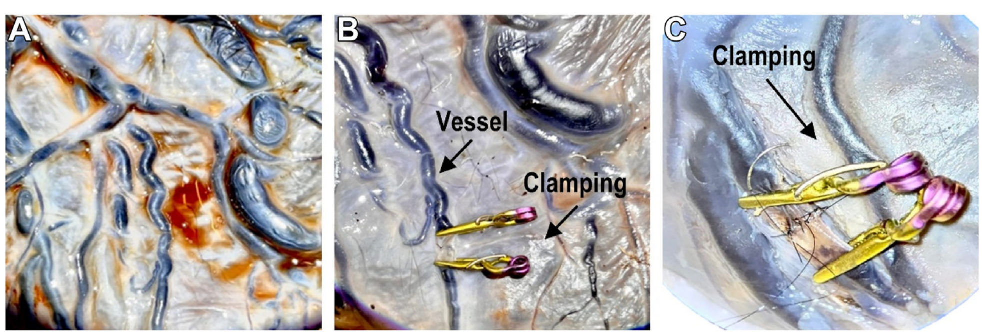


**Figure 1.** Human Placenta model. (**A**) Vessels of third bifurcation. (**B**) Chorioamniotic barrier of vessel is dissected, proximal and distal clip is placed with transverse arteriotomy. (**C**) End-to-end anastomosis.

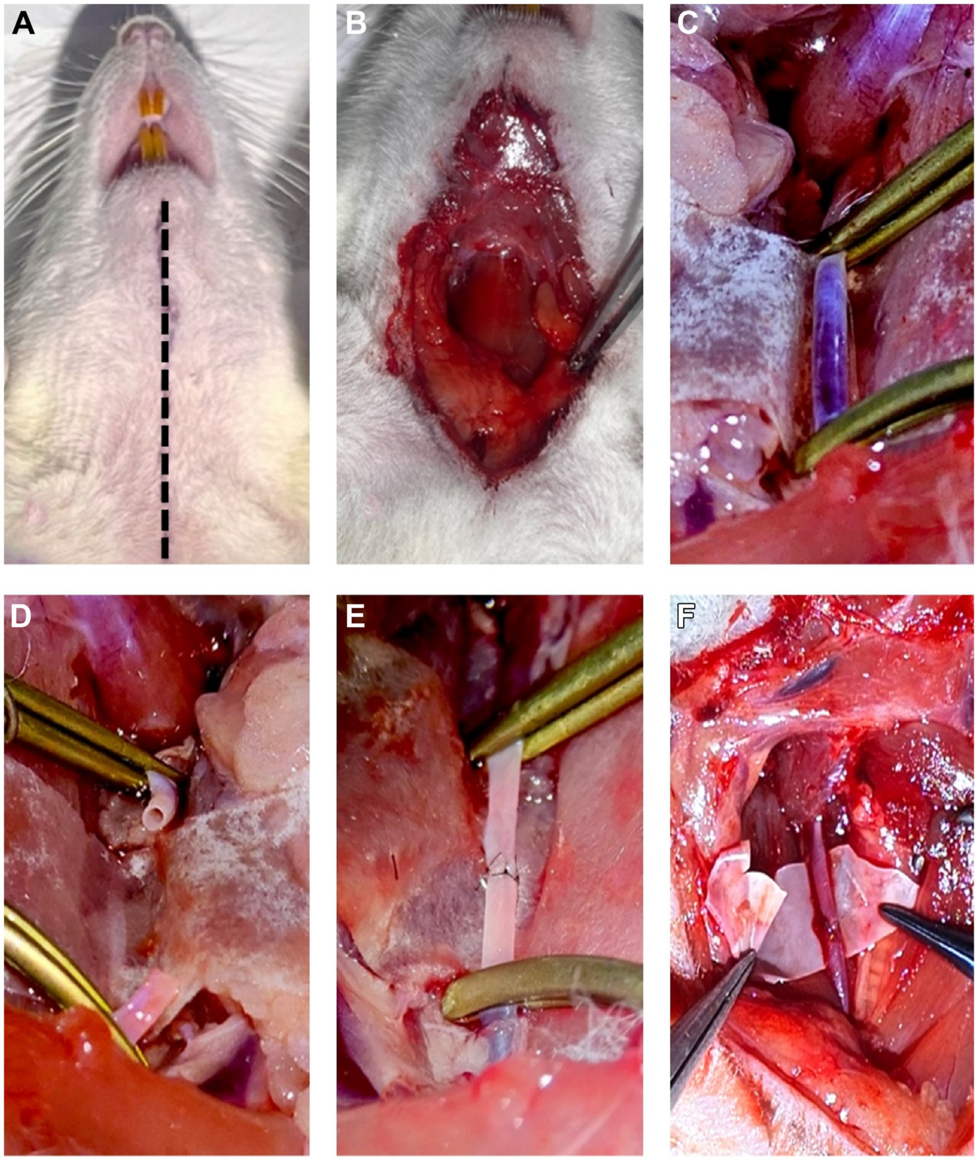


**Figure 2.** Wistar Strain Rat model. (**A**) Marking of incision from mandibular symphysis to sternal manubrium. (**B**) Exposure of sternohyoid and sternocleidomastoid. (**C**) Proximal and distal clamping of carotid artery. (**D**) Transverse arteriotomy. (**E**) End-to-end anastomosis. (**F**) Vascular permeability is checked without leaks.

## Ethical Concerns

The Faculty of Pharmacy and Biochemistry Ethics Committee of the Institute of Medical Sciences approved the experimental work. The care standards described by the "International Guiding Principles for Biomedical Research Involving Animals," written by the CIOMS and by the ICLAS, Geneva 2012, were followed.

We obtained the human placenta after approval from the Ethics and Teaching Committee, the Pathological Anatomy Service, and the Obstetrics and Gynecology and Service of the Petrona V. de Cordero Hospital in Buenos Aires.

## RESULTS

The results shown below were composed of the results obtained from the main characteristics and their scores, the advantages and disadvantages, and finally, the ES.

## Model Preference Analysis and Participant Demographics

The evaluation results highlighted several aspects, including model preferences. Notably, 91% of participants favored biological models, with 54.54% preferring the Rodent model and 34.36%

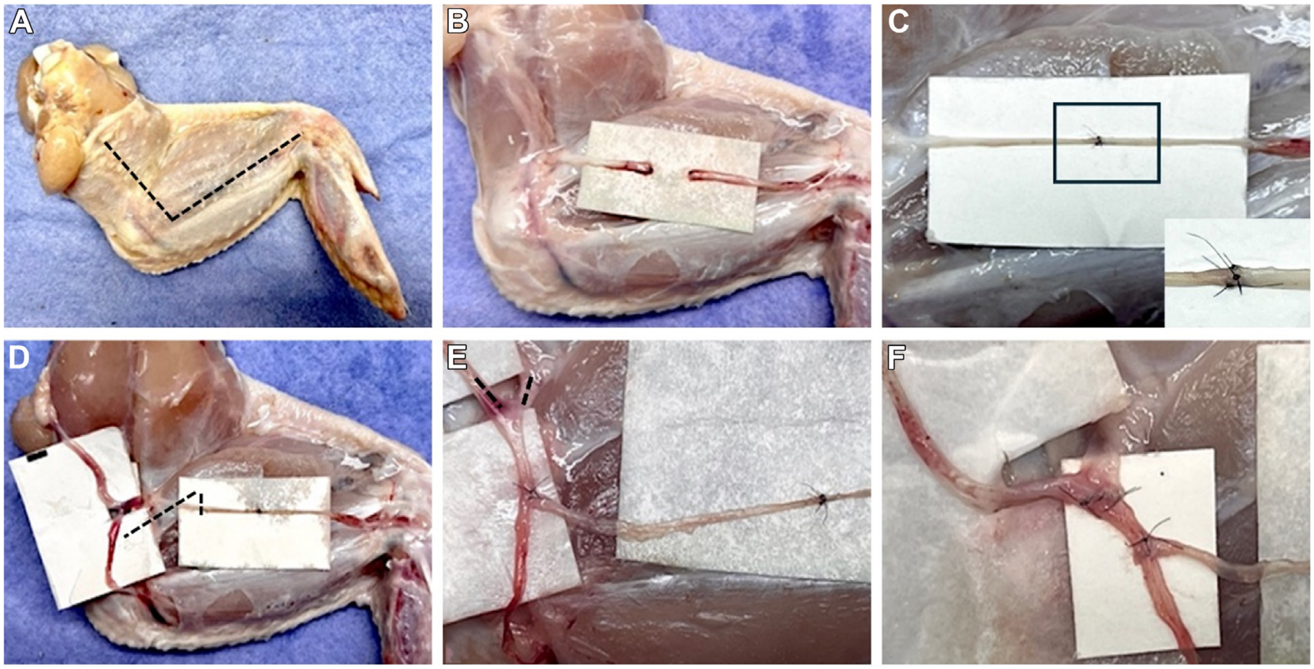


**Figure 3.** Chicken Wing Artery model. (**A**) Incision is marked for skin dissection. (**B**) Location of radial artery and transverse arteriotomy is performed. (**C**) End-to-end anastomosis 9—0. (**D**) Dissection of brachial artery and transverse arteriotomy is performed on radial artery for end-to-side anastomosis with brachial artery. (**E**) End-to-side anastomosis. (**F**) Side-to-side anastomosis of brachial and subscapular artery.

preferring the Human Placenta model. In contrast, only 9% of participants considered the UpSurgeOn model their preferred choice. Additionally, the majority of participants were from Mexico (12), Argentina (3), and Brazil (2). The distribution included 8 neurosurgery residents, 8 vascular or endovascular fellows, and 6 neurosurgeons (Figure 6). Additionally, the cost of each model was taken into consideration (Table 1).

## Main Characteristics, Advantages, and Disadvantages

Table 2 shows the total score obtained after evaluating the main characteristics.

Figure 7 shows the results of the MSC, where the total score (66 points as the maximum rating) was considered for both positive and limiting factors. This scale was used to determine which model, based on qualitative aspects, the participants considered to have the highest qualities or which models were considered limited. For this purpose, models that received a high rating in positive characteristics were associated with models having outstanding aspects for practice. In contrast, models with a high score in limiting characteristics were considered models with a high rate of practical or methodological difficulties.

***Human Placenta.*** *Characteristics.* This model was the second most chosen among participants, with high ratings for various simulation scenarios for different bypass techniques (18/22) and substantial similarity to cerebral arteries (15/22). However, its main limiting factors were found to be an increased risk of biological contamination (14/22) and challenges in obtaining ethics committee approval (6/22). Regarding the MCS obtained for this model, the score for positive characteristics was the second highest (35 points, standard deviation [SD] = 6.94), while its limiting characteristics also ranked second (23 points, SD = 4.64). This indicates that, despite being considered a model with outstanding qualities for practice, it is also regarded as a model with significant methodological implications.

*Advantages.* The texture and resistance of the placental vessels are similar to those of the cerebral vessels, making them ideal for tissue-handling training. Placentas are biological materials readily available in health institutions and do not require specific infrastructure for their management and conservation. This allows for practicing various bypass techniques, simulating different thicknesses of cerebral arteries in a single model.

*Disadvantages.* Ethical or legal restrictions may limit access to human placentas. They also require special care for their preservation and storage in order to maintain their viability. Additionally, the anatomical variability between placentas may limit the uniformity of the training material, and there is a risk of biological contamination.

***Rodent Model (Wistar Strain Rat).*** *Characteristics.* This was the most chosen model among participants, showing strong similarity to cerebral arteries (11/22) and a variety of simulation scenarios for different bypass techniques (8/22). However, despite being the preferred model, it was limited by the need for specific

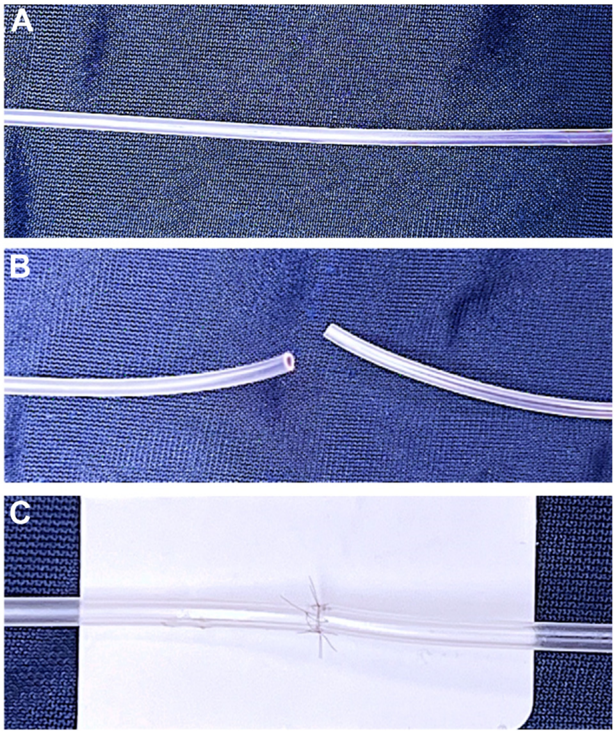

**Figure 4.** Synthetic Tube model. (**A**) Nasogastric feeding probe for premature infants 2 mm. (**B**) Transverse cut of the same simulating transverse arteriotomy. (**C**) End-to-end anastomosis with 9–0 nylon.

infrastructure for model handling (17/22), approval from ethics committees (14/22), and an increased risk of biological contamination (10/22). Analyzing its MCS, this model indicates a relatively acceptable rating in positive aspects (21 points, SD = 3.74), but it has the highest rating in limiting characteristics (41 points, SD = 2.87). This suggests that while it is optimal for practice, its limitations could hinder the utilization of this model.

*Advantages.* The similarity in texture and resistance of blood vessels to humans facilitates training in managing live tissue. It allows the ability to simulate a variety of bypass intervention scenarios, both in the carotid and femoral regions. Additionally, this enables the verification of the bypass's hemodynamic functionality, as the rat's carotid artery is similar in diameter to an M4 branch of the human middle cerebral artery.

*Disadvantages.* Using live animals implies significant ethical considerations, requiring adherence to formal management and care protocols. There is also a need for heparin to prevent bypass thrombosis and a trained team to manage the anesthesia and sedation process. Furthermore, there is a global trend toward reducing the use of animals in research and training, motivated by stricter ethical guidelines.

***Chicken Wing Artery.*** *Characteristics.* In this model, the consideration of similarity to cerebral arteries (7/22) and a relative variety of simulation scenarios for different bypass techniques (5/22) stood out exclusively. However, an increased risk of biological contamination (4/22) was identified as a limiting factor. Considering its MCS, this model had the lowest score in positive characteristics (14 points, SD = 2.05) and a low score in limiting factors (4 points, SD = 1.89). This indicates that while this model was deemed less outstanding compared to other biological models, it also showed the fewest methodological or procedural limitations among these models.

*Advantages.* The materials are economical and easy to handle and obtain, which facilitates their use in training environments. No specific facilities or anesthesia are required to keep live animals, simplifying logistical management. The diameter and structure of the arteries in the chicken wing are comparable to those of human cortical vessels, allowing representative anastomoses to be performed as done in humans.[14] This model does not require

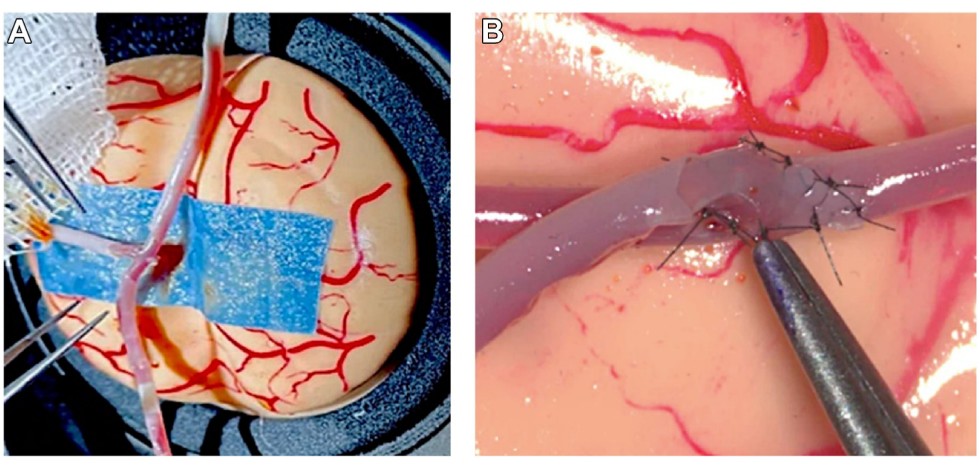

**Figure 5.** UpSurgeOn Mycro model. (**A**) Preparation of the equipment and synthetic blood vessels. (**B**) End-to-end anastomosis.

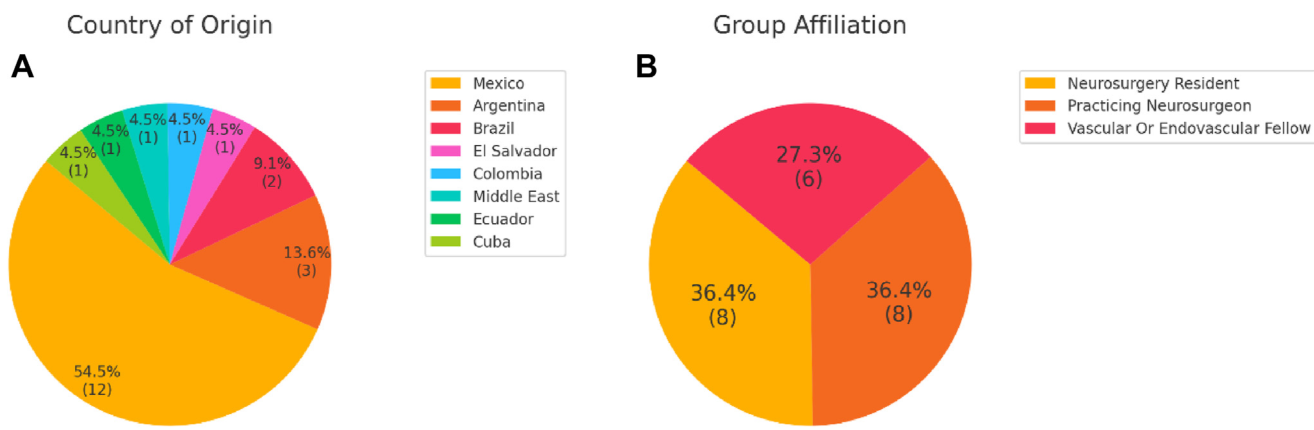


**Figure 6.** Distribution of participants. (**A**) The distribution of the participants' nationalities and their percentage of participation in the neurosurgery workshop. (**B**) Distribution of the participants' medical affiliations.

approval from institutional ethics committees, laboratory technicians, or ethics committees, streamlining the implementation process in training.

*Disadvantages.* The model presents a limited durability time due to the natural decomposition of biological tissues. It does not allow the verification of the hemodynamic permeability of the anastomoses in an extended way, which could limit its applicability in long-duration simulations.

***Synthetic Tube Model.*** *Characteristics.* This model stood out primarily for its durability for subsequent training (11/22), with its only limitation being the potential increase in risk of biological contamination (2/22). Its MCS showed that the positive characteristics were not outstanding (18 points, SD = 3.56), but it did have the lowest rating in limiting factors (2 points, SD = 0.94). This indicates that while this model lacks experimental qualities, it presented the fewest risks or complications during practice.

*Advantages.* The materials used are low-cost and easy to acquire, allowing economical access to resources for surgical training. This setup allows repeated practice and the application of various bypass techniques, facilitating standardized and controlled training. These models are suitable for training in different simulated scenarios, simulate varied sizes of blood vessels, and are reusable and easy to store.

*Disadvantages.* Although the probes allow for the simulation of the diameters of blood vessels, they do not reproduce the texture, flexibility, or the 3 layers that make up a natural blood vessel, limiting the realistic experience. The model's simplicity may require more challenges to develop the advanced sensory and motor skills necessary for complex surgical procedures.

**Table 1.** Operational Costs of Each Model

| Model | Unit Cost [USD] | Number of Participants per Unit |
|---|---|---|
| Human Placenta | 0 | 4 |
| Rodent (Wistar strain rat) | 90 | 2 |
| Synthetic Tube | 1 | 1 |
| Chicken Wing Artery | 0.5 | 1 |
| UpSurgeOn (materials) | 360 | 10 |

Prices are given in US dollars per experimental unit (per sample used for experimentation) and the number of participants that can use each unit.

***UpSurgeOn.*** *Characteristics.* This synthetic model was the preferred choice among practitioners. Despite its requirement for specific infrastructure for model handling (3/22), it was considered highly durable for subsequent training (16/22). Additionally, it was perceived to have significant similarity to cerebral arteries (12/22) and a wide variety of simulation scenarios for different bypass techniques (12/22). Analyzing the MCS scores, this model stands out for having the highest rating in positive characteristics (40 points, SD = 1.89) and a meager rating in limiting factors (3 points, SD = 1.43). This indicates that it is a model with high experimental qualities and low procedural risk, making it the model of choice based on the MCS values.

*Advantages.* The model provides a high degree of anatomical realism, with silicone tubes that simulate the adventitia layer of the vessels, which is crucial for training in neurosurgery. It allows neurosurgeons in training to practice and perfect their skills in an environment that faithfully replicates cerebral and vascular anatomy. The model offers the opportunity to gain practical experience in a controlled and safe environment before performing interventions on actual patients. Additionally, it provides immediate feedback on the techniques used, helping surgeons identify areas for improvement and perfect their surgical skills.

*Disadvantages.* The acquisition and maintenance of the UpSurgeOn model can be costly, which could limit its availability for institutions or training programs with restricted budgets. It requires regular maintenance to maintain its anatomical realism

**Table 2.** Evaluation of the Main Characteristics in Each Model

| | Models | | | | |
|---|---|---|---|---|---|
| Main Characteristics | Human Placenta | Rodent (Wistar Strain Rat) | Synthetic Tube | Chicken Wing Artery | UpSurgeOn |
| Positives | | | | | |
| Durability for subsequent training | 2 | 2 | 11 | 2 | 16 |
| Similarity to cerebral arteries | 15 | 11 | 3 | 7 | 12 |
| Variety of simulation scenarios for different bypass techniques | 18 | 8 | 4 | 5 | 12 |
| Limiting | | | | | |
| Increased risk of biological contamination. | 14 | 10 | 2 | 4 | 0 |
| Requires approval from ethics committees. | 6 | 14 | 0 | 0 | 0 |
| Requires specific infrastructure for model handling. | 3 | 17 | 0 | 0 | 3 |

The Table shows the top 6 parameters evaluated for each model, considering n = 22 per characteristics. The highest possible score for each characteristic was 22, and the lowest was 0.

and functionality, which implies additional costs. Although the model offers a high degree of simulation, it cannot fully replicate the exact texture and behavior of real human tissues.

Participants also provided qualitative feedback, noting that biological models offered a more realistic simulation experience, crucial for developing practical surgical skills. However, these models also presented challenges related to ethical approvals and the need for specific handling infrastructure. Finally, based on the results of each model's characteristics, advantages, disadvantages, and price, a comparative table of each model was considered (Table 3).

## Evaluation of the Models

Regarding the final rating for each of these models, statistical analysis was conducted using the Kruskal-Wallis H-test due to its nonparametric nature and small sample size. The test revealed a

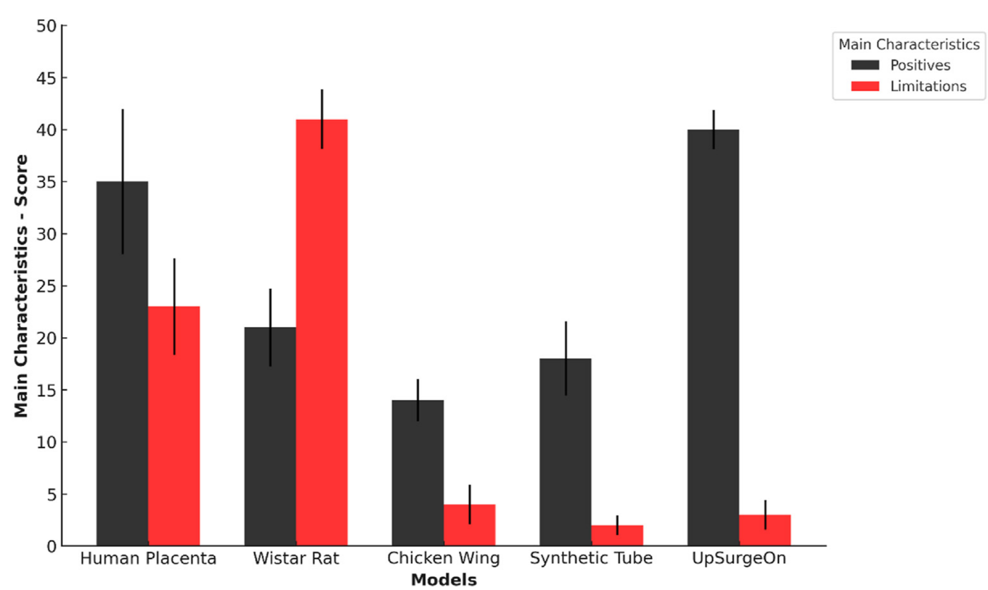


**Figure 7.** Values of the Main Characteristics Score (MCS). This graph shows the MCS values, with positive characteristics displayed in black and limiting characteristics in red for each evaluated model. Error bars represent the standard deviations.

**Table 3.** This Table Provides a Comprehensive Comparison of Various Training Models used for Intra-Extracranial Cerebral Bypass Procedures

| Model | Positive Characteristics | Limiting Characteristics | Advantages | Disadvantages | Cost per Participant [USD] |
|---|---|---|---|---|---|
| Human Placenta | Variety of simulation scenarios, similarity to cerebral arteries MCS: $35 \pm 6.94$ | Risk of biological contamination, ethical approval needed MCS: $23 \pm 4.64$ | Similar texture to cerebral vessels, no specific infrastructure needed | High risk of contamination, ethical restrictions | 0 |
| Wistar Rat | Similarity to cerebral arteries, variety of simulation scenarios MCS: $21 \pm 3.74$ | Specific infrastructure required, ethical considerations MCS: $41 \pm 2.87$ | Realistic blood flow, similar texture to human vessels | Ethical issues, infrastructure needed | 45 |
| Chicken Wing Artery | Economical, easy to handle MCS: $14 \pm 2.05$ | Limited durability, no hemodynamic permeability verification MCS: $4 \pm 1.89$ | Easy to obtain, cost-effective | Limited durability of tissues | 1 |
| Synthetic Tube | High durability for repeated training MCS: $18 \pm 3.56$ | Lacks realistic texture and behavior of natural vessels MCS: $2 \pm 0.94$ | Low cost, reusable | Not realistic texture or behavior | 0.5 |
| UpSurgeOn | High anatomical realism, variety of simulation scenarios MCS: $40 \pm 1.89$ | Specific infrastructure required, higher cost MCS: $3 \pm 1.43$ | Safe, controlled training environment, high degree of realism | High cost, specific infrastructure needed | 36 |

Each model is evaluated based on its positive characteristics, limiting characteristics, advantages, disadvantages, and cost per participant.
MCS, main characteristics score.

significant difference among the groups ($H = 28.734$, $P = 8.85 \times 10 - 6$, $\alpha = 0.05$).

A post hoc Dunn's test with Bonferroni correction identified specific group differences ($P < 0.05$), allowing us to categorize the models into 3 statistically distinct groups (Figure 8). The Wistar Strain Rat model (8.33, SD = 1.20), the Human Placenta model (8.00, SD = 1.67), and the UpSurgeOn model (7.00, SD = 1.70) received the highest ratings in ES, indicating that participants chose these 3 models as the best based on the experience gained.

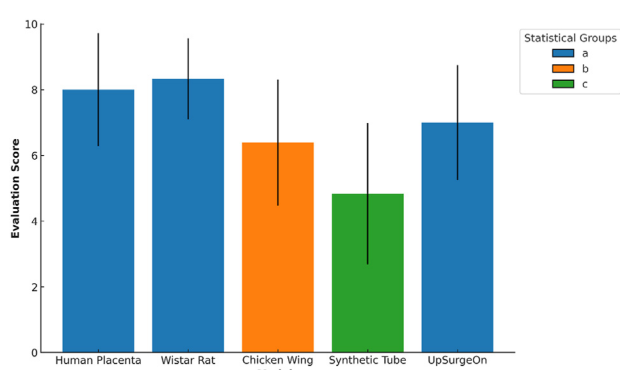


**Figure 8.** The error bar plot visually represented the mean scores and standard deviations, with color coding to highlight these statistical differences. This analysis provides valuable insights for selecting the most effective training models for the surgical course.

## DISCUSSION

Revascularization is a crucial treatment choice for dealing with complicated conditions such as Moyamoya disease, large aneurysms, and skull base tumors.[1] The increasing significance of training models in intra-extracranial cerebral bypass is widely acknowledged due to their ability to enhance surgical accuracy and safety within a controlled setting. The research conducted by Higurashi et al. (2014) and Srinivasan et al. (2001) emphasizes the effectiveness of these models in developing crucial microsurgical skills in neurosurgery. These models closely resemble actual clinical conditions and allow the practice of complex techniques without endangering patients.[11,15]

At present, microneurovascular bypass is rare for treating cerebrovascular disease since cerebral revascularization operations are limited.[14] The limited availability of these treatments in clinical practice emphasizes the crucial significance of laboratory models for regular training. These models address the absence of clinical chances and offer a secure setting for learning and practicing, which is crucial for attaining expertise in intricate procedures like cerebral revascularization.[16] As a result, neurosurgery training programs must implement a methodical strategy that includes simulations and repeating exercises to ensure that surgeons are proficient in all aspects of learning.

Therefore, this study evaluated various aspects of training models for intra-extracranial cerebral bypass (4 were microvascular anastomosis training adapted to the cerebral bypass approach). Our results suggest that the Human Placenta and the UpSurgeOn system are the best models for intra-extracranial bypass training due to their high scores in positive characteristics and ES.

The results of our study coincide with those of previous publications. Oliveira's research from 2018 concluded that the human placenta's vascular anatomy offers great similarity with the branching patterns of the main brain vessels.[8] Another study published in 2016 validated the use of the human placenta model for microvascular anastomosis training since the arteries of this model are identical to those of the human brain in wall thicknesses, amounts of connective tissue fibers, and diameters.[17] These findings are relevant since micro-neurovascular bypass is rare in real-life practice, bringing about fewer opportunities to improve the learning curve of neurosurgery residents and remarking the high necessity of laboratory models for regular training.[14] Additionally, this model proved to be extremely cost-effective, as obtaining this biological material did not incur any expense, making it, along with the chicken wing model, the top choice regarding cost-benefit; also adding that this model has the particularity of being able to reuse biological material that in most cases is discarded.

Our study also found that the UpSurgeOn training system was highly regarded among participants. This simulator has been previously validated for intracranial aneurysm clipping and for endoscopic transsphenoidal approach.[18,19] However, to date, no studies have assessed the UpSurgeon simulator for intra-extracranial cerebral bypass training. In our study, this model received the highest MCS, making it the model of choice for the recruited trainees. Therefore, this model provides safe, ethical, and highly effective training in cerebral bypass and microvascular anastomosis. Despite initial perceptions regarding its cost and required infrastructure, the long-term benefits and absence of biological limitations make it an optimal model for developing advanced surgical skills.[18,20]

A relevant limitation of our study is that we did not evaluate different simulation-based scenarios of brain bypass. Belykh et al. assessed 3D printing training models for cerebrovascular bypass for 7 different procedures replicating microanastomosis in narrow, deep-operating corridors, validating these models in resemblance to real-life surgery and ability to improve bypass technique, instrument handling, and surgical technique.[21] Future research should evaluate the biological and synthetic models under a wider spectrum of brain bypass scenarios, improving the learning curve in neurosurgery residents with simulations that require different levels of dexterity.

On the other hand, although the Wistar rat, chicken wing artery, and synthetic tube models may offer anatomical advantages (in the case of the Wistar rat) or advantages in terms of accessibility and cost,[22-24] their limitations are significantly reflected in several aspects. These limiting factors may hinder crucial elements necessary to ensure effective and safe training in intra-extracranial shunt techniques. Moreover, despite the Wistar rat being the most common choice among participants and having the highest ES, its exclusion is justified as it is the model with the greatest limitations and highest cost per unit.

Another important consideration of our study is that we implemented our own questionnaire to have a qualitative evaluation of the bypass models, while anastomosis performance was not objectively assessed. In 2015, Aoun et al. published a study validating the Northwestern Objective Microanastomosis Assessment Tool (NOMAT), a 14-item Likert-type scale that evaluates technical aspects of microanastomosis performance.[25] Future studies should evaluate trainee's performance with the NOMAT scale to have an objective assessment of a successful microanastomosis performance, further improving the validity of both biological and training models.

Finally, we consider that neurosurgical training particularly applies to the four-stage learning model devised by Noel Burch in 1970.[26] This paradigm facilitates the gradual growth of the surgeon, starting from a lack of awareness of their ineptitude and progressing into a state of skillful competence without conscious effort. It highlights the significance of repetition and purposeful practice in internalizing intricate abilities. Every phase of Burch's model emphasizes an essential milestone in the journey toward proficiency, emphasizing that achieving complete mastery of surgical skills necessitates comprehending and honing procedures and internalizing them to the point of near-automatic execution. Thus, neurosurgery training programs must implement a methodical strategy that includes simulation-based learning and repetitive practice to ensure surgical expertise.

## CONCLUSION

Our study suggests that the Human Placenta and the UpSurgeOn system are the best models for intra-extracranial bypass training. Despite some limitations, these models exhibit positive characteristics, cost-effectiveness, and valuable training experience.

We encourage future research efforts to evaluate these models for a wider spectrum of anastomotic models under different simulation-based scenarios and to assess trainee's performance with validated tools, improving neurosurgeon's learning curve and enhancing neurosurgical education.

## CRediT AUTHORSHIP CONTRIBUTION STATEMENT

**Thania de Oca-Mora:** Supervision, Methodology, Investigation, Conceptualization. **Carlos Castillo-Rangel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision. **Gerardo Marín:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation. **Cristofer Zarate-Calderon:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis. **Jonathan Samuel Zúñiga-Cordova:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Daniel Oswaldo Davila-Rodriguez:** Writing – original draft, Methodology, Investigation, Conceptualization. **Helen Ruvalcaba-Guerrero:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Valeria Forlizzi:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Matias Baldoncini:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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