



Superiority of living animal models in microsurgical training: beyond technical expertise

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Abstract

Background Many studies are investigating the role of living and nonliving models to train microsurgeons. There is controversy around which modalities account for the best microsurgical training. In this study, we aim to provide a systematic literature review of the practical modalities in microsurgery training and compare the living and nonliving models, emphasizing the superiority of the former. We introduce the concept of non-technical skill acquisition in microsurgical training with the use of living laboratory animals in the context of a novel proposed curriculum.

Methods A literature search was conducted on PubMed/Medline and Scopus within the past 11 years based on a combination of the following keywords: “microsurgery,” “training,” “skills,” and “models.” The online screening process was performed by two independent reviewers with the Covidence tool. A total of 101 papers was identified as relevant to our study. The protocol was reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.

Results Living models offer the chance to develop both technical and non-technical competencies (i.e., leadership, situation awareness, decision-making, communication, and teamwork). Prior experience with ex vivo tissues helps residents consolidate basic skills prior to performing more advanced techniques in the living tissues. Trainees reported a higher satisfaction rate with the living models.

Conclusions The combination of living and nonliving training microsurgical models leads to superior results; however, the gold standard remains the living model. The validity of the hypothesis that living models enhance non-technical skills remains to be confirmed.

Level of evidence: Not ratable.

Keywords Microsurgery · Training models · Nonliving models · Technical skills · Non-technical skills

Introduction

Many studies are investigating the role of living and nonliving models to train microsurgeons. In the current literature, there is controversy around which modalities account for the best

microsurgical training. Living models include live animals used in the laboratory for research and/or experiments. Nonliving models are subdivided in the following categories: (a) non-vital, such as chicken wing/thigh [1] or aorta [2], porcine trotters, and human cadavers [3]; (b) prosthetic; and (c) virtual reality [4]. One major difference between these two broad categories is the lack of blood circulation in the ceased specimens. Thus, the trainee microsurgeon is unable to practice intraoperative hemostasis and postsurgical assessment of anastomotic patency (i.e., the survival of the reconstructed flap).

International consensuses on minimum standards for microsurgical courses [5, 6], minimum microsurgery case requirements [7], and several validated training models with objective structured assessment of technical skills (OSATS) have been devised to evaluate the trainees' performance in microsurgery [8–11]. The development of assessment tools for robot-assisted microsurgery (RAMS) skills is still in progress [12–15]. All of these innovative grading tools are comprehensive and reliable for assessing the students' progress

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throughout a microsurgical course [16, 17]. However, they focus solely on the technical aspects [18], such as manual dexterity, hand-eye coordination, meticulous suture placement [19, 20], speed, operative flow, motion [21], and patency of the anastomosis based on task-specific checklists [22–26].

On the other hand, non-technical skills (NTS) are equally important. Non-technical skills include five broad categories: leadership, situation awareness, decision-making, communication, and teamwork [27, 28]. Recent research has shown non-technical skills are important to successful outcomes; up to 43% of errors made in surgery can be attributed to poor communication in the operating room [29]. In the operating room, NTS rise to the forefront when completing a procedure. Without prior exposure to NTS acquisition, surgeons are left to learn these skill sets while in the operating room. The need for proper evaluation of these skills when examining and treating patients is critical. However, empirical evidence suggests that there is a gap in current microsurgical training by means of not incorporating NTS into the curriculum, and by the use of solely nonliving models by some programs.

In this study, we aim to provide a systematic literature review of the practical modalities in microsurgery training and compare the living and nonliving models, emphasizing the superiority of the living models. Also, we introduce the concept of non-technical skill acquisition in microsurgical training with the use of living laboratory animals in the context of a novel proposed curriculum.

Materials and methods

A systematic literature review was conducted in PubMed/Medline and Scopus. The keywords used to identify relevant literature in PubMed were the following: “microsurgery,” “training,” “skills,” and “models.” The filters applied were English language and articles within the past 11 years. Two independent reviewers (K.G., J.R.P.) performed the search and screening process, based on title and abstract with the Covidence tool. Irrelevant articles were screened against the following inclusion and exclusion criteria. Conflicts in the selection process were resolved by discussion between these two authors.

Inclusion criteria:

- microsurgical training models
- both living and nonliving models
- experimental studies
- English language
- studies available electronically

Exclusion criteria:

- non-microsurgical training models
- human studies

- Letters to the Editor/correspondence
- articles without an abstract or full text
- non-English articles

We focused on articles on experimental living and nonliving microsurgical training models and their effect in non-technical skill acquisition. We intend to perform a meta-analysis depending on the homogeneity or heterogeneity of the results from our study.

Results

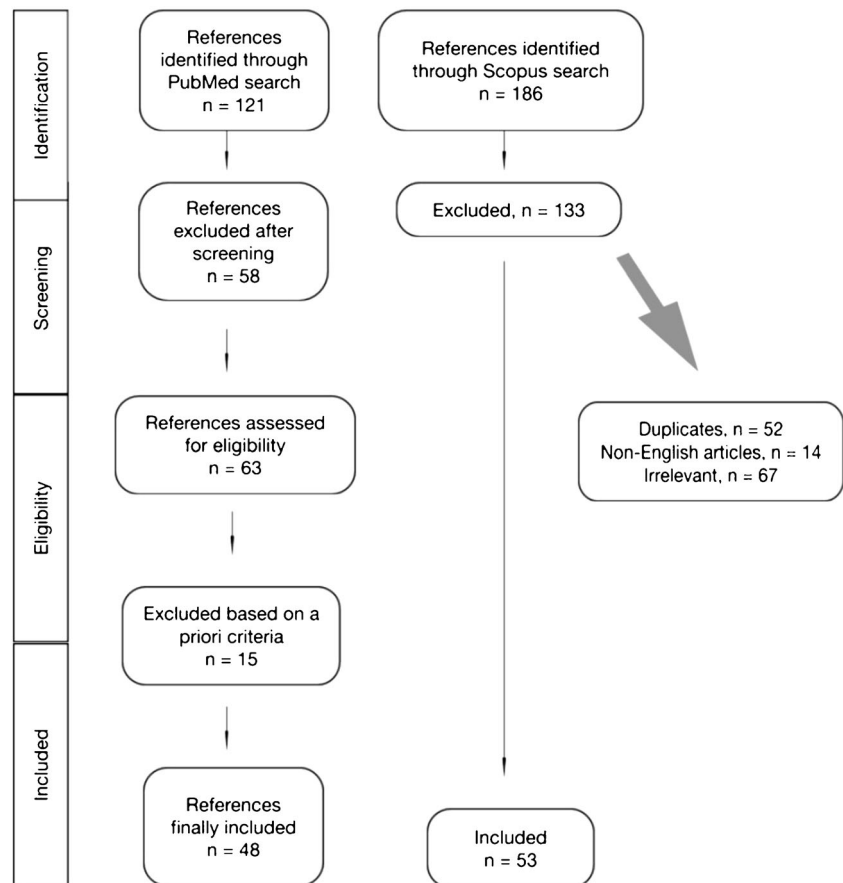
PubMed/Medline and Scopus searches between 2010 and 2020 yielded 121 and 186 papers, respectively. Upon application of filters (within the past 11 years, English language) and screening for eligibility, relevant PubMed/Medline and Scopus articles accounted for 48 and 53, respectively. A total of 101 articles was included in the study. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) algorithm is shown in Fig. 1. The study designs and methodologies were highly variable among the articles. The data retrieved were heterogeneous and could not be combined numerically. Therefore, a review was performed without a meta-analysis. For the included studies, the following information was extracted: (a) authors (year of publication), (b) demographics, (c) training modality, (d) type of skills assessed, and (e) conclusion. A summary of the major studies is described in Table 1.

Advantages of living training models

Throughout the history of microsurgery evolution, there are many outstanding examples of using live animals in experimental microsurgery. Firstly, the Nobel Prize winner Alexis Carrel (1902) performed transplantation of several organs in animals and invented the triangulation technique in vascular repair. In 1903, Hopfner was the first to report the successful mid-thigh limb replantation in a dog. In 1964, Buncke and Schulz performed the first total ear replantation in a rabbit [30]. Today, we learn from these experiments and revolutionize these techniques in human patients.

Live animal models have long been used as a means to train microsurgeons since they are considered the gold standard with many pros [31, 32]. Rats, in particular, are larger in size than mice; therefore, there is an abundance of tissues to work with and perform multiple exercises all in one specimen. That leads to a reduction in the number of live animals required, which translates to cost-effectiveness. In addition, the physiology of the rat is closer to that of the human. Established protocols in experimental surgery exist for usage of laboratory rat models in the study of virtually all anatomical systems [33, 34].

Fig. 1 The screening process as per the PRISMA algorithm



Rat vessels are a very close prototype of humane vessels that gives trainees an extra edge of competence. The trainees learn immaculate dissecting skills using hemostasis and ligating branches from main vessels. Advanced training exercises can be performed by trainees in rabbits, such as interposition vein graft [35], bypass graft, free tissue transfer (e.g., groin flap), and auricular transplantation. Apart from building technical skills faster and more efficiently under the guidance of an expert instructor [36], the presence of an experienced teacher during the execution of these exercises is fundamental in acquiring communication, teamwork, and decision-making skills.

Working with live rats simulates the operating theater experience because the rat is anesthetized. An intraperitoneal infusion of ketamine is administered before and throughout the exercises by the trainee to minimize the pain suffered by the animal. The institutions which organize living model courses are well established and have legal approval to run as per the official research ethical regulations in each country [37]. Also, a simulation environment which resembles a real operating room (OR) contributes to the engagement of the trainee. For example, operating in a theater suite scrubbed and mentally prepared to perform a challenging exercise puts the surgeon in a position of responsibility and raises pressure. This situation is difficult to generate with a do-it-yourself (DIY) device at home, even though such practice helps to

maintain basic technical microsurgical skills. Some training centers have linked the role of positive psychology and spiritual alertness with successful outcomes [37].

Preliminary studies show the detrimental effect of external stressors and cognitive distraction to the accuracy of microsurgical performance [38]. Simulation assists learners to become more dexterous and competent in controlling their level of anxiety or stress [39], thus decreasing hand tremor and improving their overall performance in simulated settings [40]. As a result, trainees begin being capable of handling challenging situations in the real clinical environment.

The living model offers the chance to develop non-technical competencies, including decision-making capacities and stress management while operating. Several examples of non-technical skills include communication with instructors and colleagues, observational learning, time management, awareness of intraoperative distractions, reflective practice, and consolidation of ethical practice (i.e., administering anesthesia and assessing for pain) [41, 42].

Due to the variability of the experimental living models, the residents learn the importance of flexibility, judgment, and readiness to make a decision. In so doing, residents develop a surgical reconstructive plan given the unique task at hand. Technical and non-technical skills attained from live rats are transferable to the human operating room.

Table 1 List of major systematic reviews on various training modalities in microsurgery

Author (year)	Type of study	Training modality	Skills assessed	Conclusion
Abi-Rafteh et al. (2019) [80]	Systematic review	Nonbiological (prosthetic models, VR)	Technical	Reduction in live experimental animals for microsurgery training
Beris et al. (2020) [31]	Descriptive study of novel proposed curriculum	Live lectures, e-learning modules, nonliving and living models, VR	Technical	Combination of teaching methods yields high performance
Brown and Rapaport (2016) [32]	Systematic review	LF and HF models	Technical	Advocates LF models as excellent alternatives to HF models
Dumestre et al. (2014) [8]	Systematic review	LF and HF models, basic and advanced	Technical	Each model offers unique training features
Dumestre et al. (2015) [25]	Systematic review	Mixture of methods	Technical (e.g., motion analysis, dexterity)	Examines types of objective assessment tools of microsurgical skills
Ghanem et al. (2013) [33]	Systematic review	Mixture of methods	Technical	Quality analysis of other studies
Javid et al. (2019) [34]	Systematic review	Mixture of methods (bench, cadaveric animal, live animal, cadaveric human, VR)	Technical	Lack of good LoE microsurgical simulators
Margulies et al. (2020) [35]	Systematic review	Interactive and passive digital resources (e.g., YouTube videos, e-learning, social media platforms, smartphone applications, VR)	Technical	Adjuncts to traditional training modalities
Pafitanis et al. (2018) [36]	Systematic review	Living and nonliving SM models	Technical	Proposed SM curriculum
Chouari et al. (2018) [3]	Experimental study	Artificially perfused fresh frozen cadavers	Technical	Significant improvement in training potential
Almeland et al. (2020) [9]	RCT	Silicone tube (microsurgery) Latex model (macrosurgery)	Technical (microscopic and macroscopic)	Poorer macrosurgical skills in medical students exposed only to microsurgical training vs both
van Mulken et al. (2018) [14]	Preclinical study	Microsure robotic system	Technical	Steeper learning curve and poorer performance with robot vs conventional method
Paladino et al. (2020) [37]	Double-center experimental cohort study	Live rats	Technical	Expert instruction enhances microsurgical performance vs self-directed practice
Alshomer et al. (2020) [38]	Proposed technological innovation (to be validated)	Novel 3D printed tool	Technical	Multiaxial/angular vessel orientation for microvascular anastomosis training simulating real clinical cases
Oliveira et al. (2018) [39]	Experimental model for neurosurgery	Ex vivo human placenta simulator	Technical	Great resemblance with brain vessels, practice bypass techniques
Malik et al. (2017) [40]	RCT	Home-based chicken femoral artery	Technical	Self-directed home-based training with either jewelers microscope or iPad has comparable results to laboratory-based training using a tabletop microscope
Yule et al. (2018) [41]	Double-center study of construct validity	Simulated surgical videos	Non-technical	Validation of NOTSS tool

LF low-fidelity, HF high-fidelity, VR virtual reality, LoE level of evidence, SM supermicrosurgery, RCT randomized controlled trial, NOTSS Non-Technical Skills for Surgeons

Discussion

Alternative nonliving models as a stepping milestone for basic skill consolidation

Microsurgery classrooms globally have recognized a principle shift toward the “3 R’s”: (1) reducing the quantity of live animals used, (2) replacing live models with virtual or classroom learning, and (3) refining experimental designs [43]. The Animals (Scientific Procedures) Act 1986 Amendment Regulations 2012, paragraph 22/20B:(4) defines alternative strategies as “scientific methods and testing strategies which do not use protected animals, or which use fewer protected animals or reduce the pain, suffering, distress or lasting harm caused to protected animals” [44].

In order to abide by these regulations, researchers and policy creators have begun to recognize and started to turn to alternative educational modalities, such as nonliving models, virtual reality/augmented reality (VR/AR) and three-dimensional tools for microvascular anastomosis training [45]. Thus, a reduction between 50 and 90% was achieved in the usage of living animal models because of enhanced skills gained through bench models prior to embarking on to the real live tissues of the rat model [46] without compromising the quality of training [47].

Other studies support that the re-use of animals or ex vivo human-based tissues, when appropriate, reduce the number of animals consumed in the microsurgical laboratories while improving basic skill sets [48]. For example, the human placenta

model of education offers the opportunity to practice during multiple sessions, since there is a multitude of vessels to work with. These vessels are prepared with macrodissection or microdissection after removal of the outer membrane of the placenta [49–51]. A myriad of novel synthetic [52] (e.g., silicone [53, 54], polyvinyl alcohol gelatin tubes [55]) and biological training models has been devised [56–58], applicable to surgical specialties (e.g., hand [59, 60], urology [61, 62], otolaryngology [63], ophthalmology [64, 65], orthopedics [66]). Another example is the ex vivo ovine model for microsurgical training on parotidectomy and facial nerve reanimation [67]. Persistent, repeated, interval [68], deliberate, self-directed practice on low-fidelity platforms are excellent alternatives to high-fidelity models [69–71]. It is found that having previous practical experience with ex vivo models enhances skill retention [70, 72], confidence [73], and cognitive perception within the operating room because the technical skills have been mastered and become automatic. Using both living and nonliving models offers the opportunity to reach the highest level of competency needed in microvascular free tissue transfer; each modality offers a unique skill set to the trainee microsurgeon [70]. Transferable skills from nonliving models are acquired and applied successfully in the live rat model [70, 74, 75]. It should be emphasized that nonliving models work as an intermediate stage to consolidate basic skills prior to embarking on more advanced exercises in the living model. This allows for multitasking and increased efficiency within the operating room [76].

Advantages of virtual reality and nonliving training models

There is no doubt that nonliving models offer several advantages. Grober et al. [41] concluded that microsurgical skills attained in low- and high-fidelity training models are equally effective for novice participants. In the current COVID-19 era, where clinical exposure for trainees is minimized, VR/AR helps sustain skills through simulated-based practice [77–81]. Following the advent of new-age VR technology, the next goal was to determine its predictive validity in human operating rooms. Virtual reality was seen as a new educational tool to both appeal to a growing movement toward minimizing live animal use, and as a new technological wave to update curricula [82].

While early results are encouraging, multidimensional VR applications have remained somewhat limited to specific subprocedures of broader operations, such as harvesting of free fibula and transplanting it for femoral head osteonecrosis. As a result, select microsurgery courses have proposed modernized curricula consisting of a blend of both live and virtual learning experiences [83]. A wealth of digital content is now readily available and easily accessible to learn microsurgery via YouTube videos, phone applications, professional websites, and academic Institutions [84].

The porcine [46] and bovine [85] hearts and the microsurgical simulation model with pulsatile flow system [86] have been devised as alternative methods of education for the trainee microsurgeon. Another example is the home-based microsurgical training model; this modality was shown to be a realistic, cheap, and reproducible tool to help the trainee microsurgeon to maintain already obtained skills [87, 88]. Another examples of a simple DIY type of simulator are the plant-based model which uses the halved stem of a chive for microsurgical anastomosis [89], the grapefruit training model for cerebral artery side-to-side microsurgical bypass procedure [90], and other innovations related to neurosurgery [91, 92]. Other considerable advantages of nonbiological microsurgical simulators include ease of setup and storage, low cost [93], low maintenance, repeated use, no risk of infectious disease transmission [82], and portability [94]. Thus, the transition from the ex vivo model to the in vivo one will be smooth for the resident [95–97].

Disadvantages of nonliving models

By working in isolation with artificial specimens, the trainee is unlikely to receive immediate feedback from an instructor, which would be deemed invaluable in building better microsurgical skills [36]. In contrast, residents are being monitored from real-time video projectors and assessed with hand motion analysis technology through sophisticated computer software [16, 98–101]. This offers an unparalleled experience of quality feedback from the instructors to the students [41]. Other microsurgical training programs incorporated electroencephalographic (EEG) monitoring to provide feedback to the trainees [102].

Nonliving models cannot replicate the physiological processes which take place within a living organism, such as thrombogenesis, natural blood flow, the real feel of the living tissues, and inflammatory processes secondary to traumatized tissues, while the trainee performs exercises and handles tissues in a rough manner. The basic structure of the vessel can be generated with technology. For instance, the adventitia and the vessel wall are possible to simulate with technology [103]; however, there is not yet a substitute for the intima and the role of the living endothelial cells [104].

Additionally, studies on andragogical and pedagogical theories support the view that trainees prefer to work with living models than nonliving tissues [95]. When it comes to training the future generation of microsurgeons, it is wise to ensure that the journey is enjoyable, and the educational techniques are standardized, well studied, and proven effective. The teaching modality should be attractive to the trainee microsurgeon in order to enhance the learning process.

Mitchell and Arora [105] stated that “knowledge, the standard of work, coping with complexity and perception of context” are the constructs of “the Dreyfus and Dreyfus model,”

which pertains to building surgical competencies. It is important to remember this andragogy model in microsurgical training because the goal is not only a vital anastomosis but also a well-rounded surgeon [105]. Decision-making constitutes most of the surgical skill, especially when it comes to raising flaps and performing more advanced microsurgical techniques. Emphasis should be placed on the right mindset, frustration, and stress management, along with interim practical sessions. A summary of pros and cons for both living and nonliving models is listed in Table 2.

Identifying the gap

While microsurgery education tools have focused on the adoption of new technology and the latest cutting-edge supermicrosurgical simulation training curricula [106–108], we contend that the development of softer skills is necessary for a surgeon in an operating room. Microsurgery is a demanding core skill set with a steep learning curve applied across a variety of specialties. Often, students in a teaching lab are encouraged to perform many procedures as respective weeklong courses; procedures are tedious and often consume the entirety of a day. As such, the work is siloed, and surgeons are left to their own devices to adapt to a new environment and successfully produce viable vessels. However, a specialist surgeon should excel in the following nine categories: teamwork, communication, health advocacy, judgment, leadership, expertise, professionalism, scholarship, and technical expertise. All these skills should be addressed when devising a training curriculum in microsurgery [109].

Here, we notice a significant discrepancy between the educational setting and the real-world operating room; practicing surgeons in an operating room are often working together with multiple technicians, assistants, and even other surgeons. As such, many of the learned skill sets surgeons take from a microsurgery teaching lab need to be adjusted for the operating room working with others [110].

In recent years, non-technical skills have been more closely examined, both retroactively and proactively. The Non-Technical Skills for Surgeons (NOTSS) system has been adopted as a tool to provide feedback to surgeons in these important non-technical skills, comprised of 14 elements that are evaluated on a 4-point scale to provide transparency to surgeons on observed operating room behaviors [29]. Given the more widespread acknowledgment for the development of surgeons' non-technical skills, we propose microsurgery labs to likewise explore opportunities to adjust to contemporary andragogy models to develop a well-rounded microsurgeon.

Bridging the gap: development of an integrated non-technical skill curriculum

We suggest classrooms are already designed to easily incorporate NTS development. Microsurgery labs are often designed for 3–6 students in a weeklong course. This provides students with the opportunity to learn from each other, in addition to individual work. The culmination of a week of microsurgery procedures could manifest in a group procedure among students using either living or nonliving subjects. The microsurgery instructor can suggest a procedure which would require the group to work together to accomplish a goal. Instructors then evaluate students across a multitude of non-technical skill measurements in order to gauge readiness for the operating theater.

Similar to how the NOTSS system has proven an effective tool for non-technical skill evaluation [111], we outline a prospective grading system for implementation in existing microsurgery courses. Our scorecard mirrors elements of the NOTSS system, though layers of both process scoring and results scoring. The aim of the system is to provide both students and instructors with repeatable and predictable processes for successful microsurgical outcomes. We devised a similar grading system of 21 elements that has been tailored and weighted to fit the demands of a microsurgeon in a real operating environment. Each student is given a role (in a team) to execute an advanced microsurgery procedure, along with

Table 2 Summary of advantages and disadvantages of experimental living and nonliving microsurgical training models

Type of models	Advantages	Disadvantages
Living models	Abundance of physiological tissues Multiple exercises in 1 specimen Hemostasis Need for anesthesia and monitoring Closer to human vessels Improved simulation experience for learners Development of NTS	Ethical concerns High cost (enrolment, maintenance) Standard precautions Steep learning curve Expert instruction often required
Nonliving models	Significant reduction of live animals Lower cost, easy setup (DIY synthetic kits) VR simulation—enhanced visuospatial skills Smooth transition to living models (transferable skills)	Low fidelity No circulation—inability to practice hemostasis Infectious diseases (e.g., human placenta) Inability to develop NTS

NTS non-technical skills, DIY do-it-yourself

Table 3 Details of a hypothetical scenario in the context of a simulated microsurgical experimental environment with a focus on non-technical skill assessment and evaluation

Category	Subcategories	Score	Feedback
Situation awareness	Gathering information, understanding situation, and anticipating the future state		
	Respecting self-limitations		
	Recognizing stress/fatigue and taking actions to mitigate these		
	Taking breaks at appropriate intervals		
	WHO checklist, “timeout,” safety first		
Communication and teamwork	Elimination distractions/interruptions within OR		
	Remaining vigilant		
	Effective clear speech		
	Accurately exchanging clinical information within multidisciplinary team		
	Asking for help timely and appropriately		
Leadership	Liaising with anesthesiologist regarding intraoperative analgesia/sedation		
	Establishing a clear shared mental model on surgical plan		
	Psychomotor skills (i.e., coordination with assistant)		
	Acting at a high standard of performance		
	Role modeling expert performance and behavior		
Decision-making	Implementing strategies for stress relief (i.e., deep breathing, visualizing successful outcome)		
	Confident leadership style		
	Setting the pace		
	Considering different reconstructive options		
	Confirming which is the right next move with instructor, if unsure		
	Executing accurately the decision made		

Scenario: You are the primary microsurgeon for the following case. You and your team are required to elevate a free groin flap and transfer it to the contralateral side with microvascular anastomosis. You are encouraged to use your assistant appropriately throughout the procedure. Another assistant is assigned the role of a “scrub nurse.” The anesthesiologist is closely monitoring the “patient” (subject). You are given 3 h to perform this task

guidelines for completion of the task (time, method, and roles). The surgeons are then asked to carry out the procedure under the parameters mentioned and to work together to accomplish the goal (Table 3). The validity of this novel assessment tool for NTS remains to be tested in a pilot cohort study.

Patient consent N/A

Informed consent N/A

Conflict of interest Konstantinos Gasteratos, Joseph Robert Paladino, Yelena Akelina, and Horacio F. Mayer declare no conflict of interest.

Conclusions

The use of artificial models has generally proved to be more cost-effective than the maintenance of an animal experimental laboratory. Every method of microsurgical training assists residents with the acquisition of a variety of skills. However, the combination of all pedagogical entities guarantees enhanced results. In a step-wise approach, it must be stressed that residents should always start practicing on simple low-fidelity models and then upgrade to more complex exercises with live models. However, training with live rats is considered the *gold standard* in the current microsurgical training. Our proposed scorecard attempts to evaluate non-technical skills. Due to the paucity of evidence in this field, future research should focus on developing curricula with integrated NTS specific to microsurgery.

Declarations

Ethical approval For this kind of article, formal consent from a local ethics committee is not required.

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