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An evaluation of physical and augmented patient-specific intracranial aneurysm simulators on microsurgical clipping performance and skills: a randomized controlled study

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OBJECTIVE In the era of flow diversion, there is an increasing demand to train neurosurgeons outside the operating room in safely performing clipping of unruptured intracranial aneurysms. This study introduces a clip training simulation platform for residents and aspiring cerebrovascular neurosurgeons, with the aim to visualize peri-aneurysm anatomy and train virtual clipping applications on the matching physical aneurysm cases.

METHODS Novel, cost-efficient techniques allow the fabrication of realistic aneurysm phantom models and the additional integration of holographic augmented reality (AR) simulations. Specialists preselected suitable and unsuitable clips for each of the 5 patient-specific models, which were then used in a standardized protocol involving 9 resident participants. Participants underwent four sessions of clip applications on the models, receiving no interim training (control), a video review session (video), or a video review session and holographic clip simulation training (video + AR) between sessions 2 and 3. The study evaluated objective microsurgical skills, which included clip selection, number of clip applications, active simulation time, wrist tremor analysis during simulations, and occlusion efficacy. Aneurysm occlusions of the reference sessions were assessed by indocyanine green videoangiography, as well as conventional and photon-counting CT scans.

RESULTS A total of 180 clipping procedures were performed without technical complications. The measurements of the active simulation times showed a 39% improvement for all participants. A median of 2 clip application attempts per case was required during the final session, with significant improvement observed in experienced residents (postgraduate year 5 or 6). Wrist tremor improved by 29% overall. The objectively assessed aneurysm occlusion rate (Raymond-Roy class 1) improved from 76% to 80% overall, even reaching 93% in the extensively trained cohort (video + AR) ($p = 0.046$).

CONCLUSIONS The authors introduce a newly developed simulator training platform combining physical and holographic aneurysm clipping simulators. The development of exchangeable, aneurysm-comprising housings allows objective radio-anatomical evaluation through conventional and photon-counting CT scans. Measurable performance metrics serve to objectively document improvements in microsurgical skills and surgical confidence. Moreover, the different training levels enable a training program tailored to the cerebrovascular trainees' levels of experience and needs.

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KEYWORDS aneurysm clipping simulator; education; cerebrovascular; surgical simulation and training

ABBREVIATIONS AR = augmented reality; ICG = indocyanine green; PGY = postgraduate year.

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Recently, the microsurgical management of standard and complex intracranial aneurysms has been challenged by the introduction of novel endoluminal and endosaccular devices. Still, clipping often remains the sole salvage treatment option for patients with complex aneurysm features. Consequently, neurosurgeons are now dealing with a decreasing microsurgical caseload, yet aneurysm clipping cases are becoming increasingly complex.[1,2] Considerable experience and years of specialty training are necessary to correctly select clip type and size and to achieve low complication rates. Even in experienced hands and elective treatment settings, intraoperative aneurysm ruptures have been described in 3% to 8% of the cases due to multiple clipping attempts, inadequate aneurysm manipulation, or unsuitable clip selection.[3,4] Moreover, the occurrence of ischemic complications resulting from inadvertent stenosis or occlusion of parent or perforating arteries and aneurysm remnants after elective unruptured intracranial aneurysm clipping procedures underlines the importance of structured education and skill training.[5–9]

Consequently, there is an unmet demand to train future cerebrovascular neurosurgeons outside the actual operating room in safely performing clipping of intracranial aneurysms. In the past, several models have been proposed to improve microsurgical skills. Such solutions included physical and digital simulators with various degrees of patient specificity, haptic feedback, anatomical deformation, and rupture functionalities.[10–14] Because of long manufacturing times, high acquisition costs, or a lack of patient specificity and objective performance metric assessment, these previous simulators have not been widely established.

We now introduce a training platform for cerebrovascular trainees and experts, consisting of newly developed physical and holographic aneurysm clipping simulators, validated in a randomized controlled study.

Methods

Physical and Augmented Patient-Specific Aneurysm Simulators

A novel additive manufacturing workflow and simulation platform was used to fabricate 5 patient-specific aneurysm phantoms as well as their concomitant holographic simulations (HoloLens 1, Microsoft Corp.). State-of-the-art technological methods in additive manufacturing and augmented reality (AR) were combined to create simulation experiences satisfying the following requirements: cost efficacy, patient specificity, perfusion pump compatibility, ultra-thin and realistic vessel wall properties, and prompt case exchangeability (Fig. 1). All aneurysm cases had been previously treated microsurgically without complications, and their preoperative neuroimaging data (DSA, CTA, and MRA) were used to fabricate 3D-printed silicone models with realistic wall thicknesses ranging from 0.39 to 0.44 mm (Spectroplast) (Fig. 2, Video 1).

VIDEO 1. Case 5. Virtual reality simulation of aneurysm clipping. Virtual clipping was performed using the HoloLens 1 system. © Philippe Dodier, published with permission. Click here to view.

The small, patient-specific housings containing aneurysms and proximal and distal vasculature were successively locked on a generic skull and connected to a voltage-controlled, low-power pump facilitating the simulation of constant perfusion and indocyanine green (ICG) application. The holographic simulations of the same cases were implemented in an AR-mounted display to test different clipping strategies and implants (finite element method simulation, Simulation Open Framework Architecture [SOFA]) (Video 1).[15]

Study Design and Randomization

This randomized controlled study received institutional ethics committee approval and was conducted in the training laboratories of our department, between April and May 2022, in accordance with local COVID-19 regulations. In a first step, three board-certified neurosurgeons with vascular expertise preselected sets of suitable (n = 2) and unsuitable (n = 8) clips for each of the 5 cases (Fig. 3, Video 2, Table S1).

VIDEO 2. Case 1. Side-by-side comparison of the original and simulated cases. The procedures were performed by the same expert neurosurgeon. Left: Microsurgical documentation of clipping of an anterior communication artery aneurysm with a sideward bent Sugita clip, followed by ICG videoangiography. Right: Same case performed on the physical simulator by the same expert neurosurgeon to define suitable and unsuitable clips (clip preselection) (Fig. 3). © Philippe Dodier, published with permission. Click here to view.

Next, 9 residents underwent a standardized training protocol adapted from Mashiko et al.[11] For each case, neuroimaging assessment of all available preoperative radiological data was performed, followed by the selection of 5 clip implants of the proposed 10 clips per aneurysm case (Fig. 3). Finally, the 9 residents performed physical clipping simulations distributed over two sessions on day 1 and 2 sessions on day 14 in a realistic, microsurgical scenario (Fig. 3). The 9 residents were randomly assigned to three cohorts and exposed to different levels of additional training (Fig. 3).[16]

Microsurgical Skills, Clip Selection, and Radio-Anatomical Outcome Measures

The results of the first (day 1, session 1) and last (day 14, session 4) of the four physical sessions, labeled as reference sessions, are compared.

Duration, Clip Selection, Clip Attempts, and ICG Videoangiography

The detailed study workflow is depicted in Fig. 3. Video recordings (OPMI Pentero, Carl Zeiss Surgical GmbH) of all simulations were collected throughout the entire study duration. After final clip application by each resident, ICG fluoroscopy (Verdye 5 mg/ml, Diagnostic Green) was performed in all cases to assess the aneurysm occlusion rate as well as parent artery patency. Objective assessment data comprised simulation durations, clipping attempts, wristwatch acceleration, clip selection matching, and occlusion rate. All data were documented by two independent assessors in the laboratory (principal investigators: P.D. and L.C.) and were a posteriori confirmed by revisualization of the video documentation.

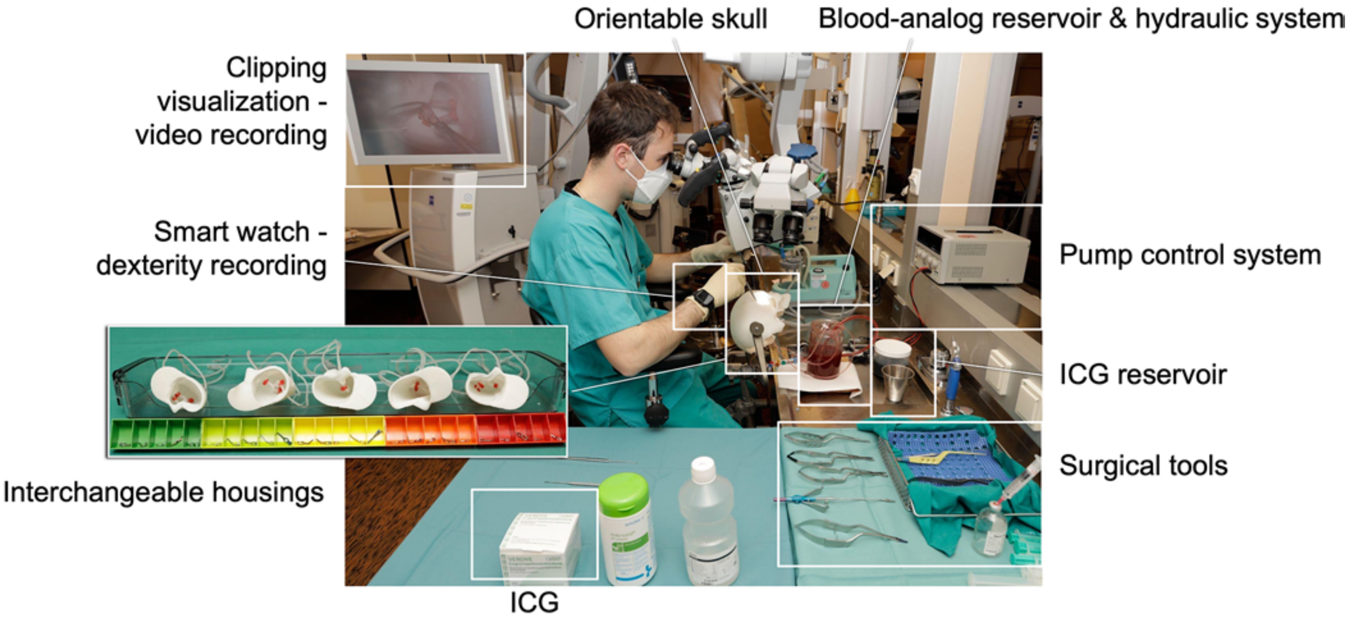

FIG. 1. Study setup and physical simulator. The skill laboratory setup comprised a 3D-printed skull allowing extended surgical access through an interchangeable interlocking mechanism with the 5 housings comprising patient-specific aneurysms. The system connected to a voltage-controlled, low-power pump facilitating the simulation of constant perfusion with a blood-mimicking liquid and ICG application. All simulation procedures were microsurgically performed using the OPMI Pentero surgical microscope. All participants had a representative collection of applicators, a total of 63 different clip models (L-clips, Peter Lazic GmbH; Sugita clips, Mizuho Medical Co., Ltd.; and Yasargil clips, B Braun Aesculap AG) at their disposal.

Wrist Tremor Measurements

The acceleration at the wrist was measured using a smartwatch equipped with a three-axis accelerometer: all residents were required to wear it on their dominant, clip-applying wrist over the surgical glove with an adjustable rubber strap (Apple Watch Series 5, Apple Inc.) (Fig. 1). The acquisitions were then refined, keeping only the moments of transmission of force to the aneurysm, i.e., when the clip was in contact with the aneurysm model. The data were then filtered to keep the frequencies responsible for wrist tremor ranging from 1 to 20 Hz, and retrospectively used to calculate the total power, peak power, and peak frequency.[17,18]

Final Radio-Anatomical Outcome

The qualitative evaluation involved the assessment of the radio-anatomical outcome and correct application of the selected clips based on standard and photon-counting CT scans (Siemens Emotion and Naeotom Alpha scanners). The radio-anatomical aneurysm occlusion was assessed according to the Raymond-Roy classification by two independent radiologists.[19] They investigated the final clip position in relation to the aneurysm neck on multiplanar reformatted images as well as 3D rendering (Fig. 4).

Statistical Analysis

For descriptive statistics, the chi-square or Fisher exact test was used, as appropriate. The Kruskal-Wallis test and Mann-Whitney U-test were used to assess differences in baseline values among the three groups at day 1/session 1. Significant p values were corrected for multiple testing by the Shaffer procedure. Wilcoxon signed-rank tests for paired samples were used to evaluate metric or ordinal data of session 1 in comparison with session 4 among the study population and separated for the three cohorts. Two-sided p values < 0.05 were considered statistically significant. Two-sided p values < 0.1 were reported as a trend because of the smaller sample size in our prospective randomized study. IBM SPSS version 28.0 (IBM Corp.) was used for data administration and statistical calculations. Graphs were prepared using Prism for Windows version 9.5.0 (GraphPad Software).

Results

General Resident Characteristics

The overall female-to-male ratio was 1:8; consequently, sex is not reported due to the small study sample allowing for the potential identification of participants. All residents were right-handed, were nonsmokers, and had not performed microsurgical aneurysm clipping as the leading surgeon before.

Duration of Physical Clipping Simulation Sessions

The cumulative active simulation time declined between both reference sessions (Fig. 5A, Table 1). Before evaluating the impact of training on the active clipping simulation time, we compared the baseline results of day 1/session 1 between the three cohorts. Cohort 3 already showed significantly lower baseline results of active simulation time during session 1 in comparison with the other cohorts (cohort 1 vs cohort 3: $p = 0.001$; cohort 2 vs cohort 3: $p = 0.033$) (Fig. 5B). Despite this difference in the base-

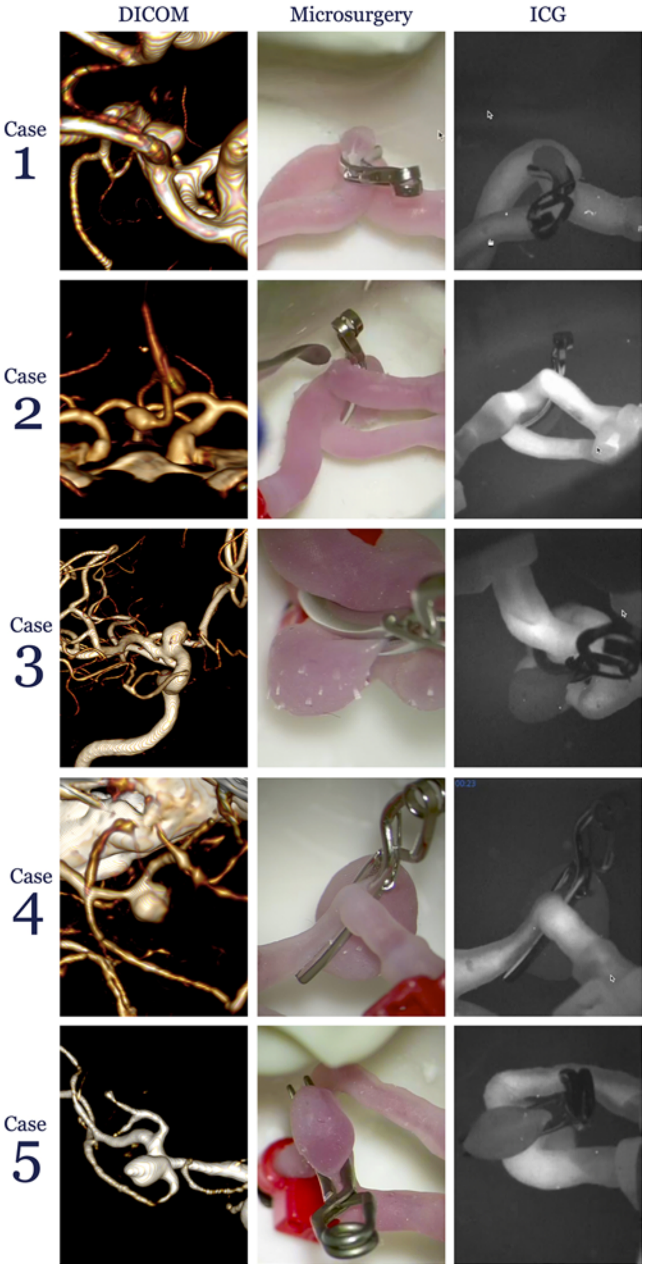

FIG. 2. Overview of all 5 aneurysm cases. All aneurysm cases had been previously treated microsurgically and electively without complications, and their preoperative neuroimaging data were used to fabricate 3D-printed silicone models with realistic wall thicknesses ranging from 0.39 to 0.44 mm. Case 1. Aneurysm of the anterior communicating artery, 5-mm dome diameter, 3-mm neck diameter. Case 2. Aneurysm of the anterior communicating artery, 8-mm dome diameter, 6-mm neck diameter. Case 3. Aneurysm of the right internal carotid artery, 6-mm dome diameter, 5-mm neck diameter. Case 4. Aneurysm of the right middle cerebral artery (M3), 8-mm dome diameter, 5-mm neck diameter. Case 5. Aneurysm of the right middle cerebral artery, 6-mm dome diameter, 5-mm neck diameter.

line results, the overall median active clipping simulation time per case improved from 70 to 43 seconds between sessions 1 and 4, corresponding to a 39% increase in time efficacy throughout the study (Table 1).

Next, duration times between sessions 1 and 4 were compared among the different training cohorts. We observed a significant decrease in the active simulation time between sessions 1 and 4 among cohort 1 (control) (p = 0.023) (Fig. 5B, Table 1). Although cohort 2 (video) improved in the median active simulation time between sessions 1 and 4, statistical significance was not reached (Fig. 5B). The subgroup analysis of the impact of any additional training on the active simulation time of pooled cohorts 2 (video) and 3 (video + AR) failed to demonstrate significant changes between the reference sessions (Fig. 5C).

Clipping Attempts

The overall number of clipping attempts improved between sessions 1 and 4 with a reduction of 26% across all cohorts (p = 0.062) (Fig. 5D, Table 1). While the median number of clipping attempts improved from 3 to 2 per case in cohort 1, it remained constantly low throughout the course of the study in cohorts 2 and 3, with a median of 2 attempts per case (Fig. 5E). The subgroup analysis of the level of education revealed that postgraduate year (PGY) 5 and 6 residents improved significantly throughout the course of the study, with a median of 3 attempts per case and a 49% overall improvement (p = 0.028) (Fig. 5F, Table 1).

Wrist Tremor Measurements

Before evaluating the impact of training on wrist tremor, we compared the baseline results of day 1/session 1 between the three cohorts. Cohort 3 already demonstrated significantly lower baseline kinematic values during session 1 in comparison with the other two cohorts (cohort 1 vs cohort 3: p = 0.012; cohort 2 vs cohort 3: p = 0.040) (Table 1). Still, an overall improvement of 26% for all 9 participants was achieved between sessions 1 and 4 (Fig. 5G, Table 1).

Next, wrist tremor measurements between sessions 1 and 4 were compared among the different additional training cohorts. Although not statistically significant, the crude data demonstrate an improvement of 29% for cohort 2 (video) and 40% for cohort 1 (control) between both reference sessions (Fig. 5H, Table 1). Of note, the subgroup of PGY-5 and PGY-6 residents improved significantly between both reference sessions, with a 51% reduction of involuntary surgical tool movement during session 4 (p = 0.027) (Table 1).

Clip Selection and Final Clip Application

The clip selection match was rated as the degree of accordance between the expert preselection and the choice of implanted clips by the participants. In reference sessions 1 and 4, 90 clipping procedures were simulated. The residents achieved an overall final implant match with the experts' clip selection of 70% (63/90). The final implant match improved between reference sessions 1 and 4 from 64% to 76%.

All cohorts presented either improved or stable results in the final session: cohort 1 (control) reached a match of 67% in session 1 versus 93% of suitable clips in session 4, cohort 2 (video) improved from 53% in session 1 to a

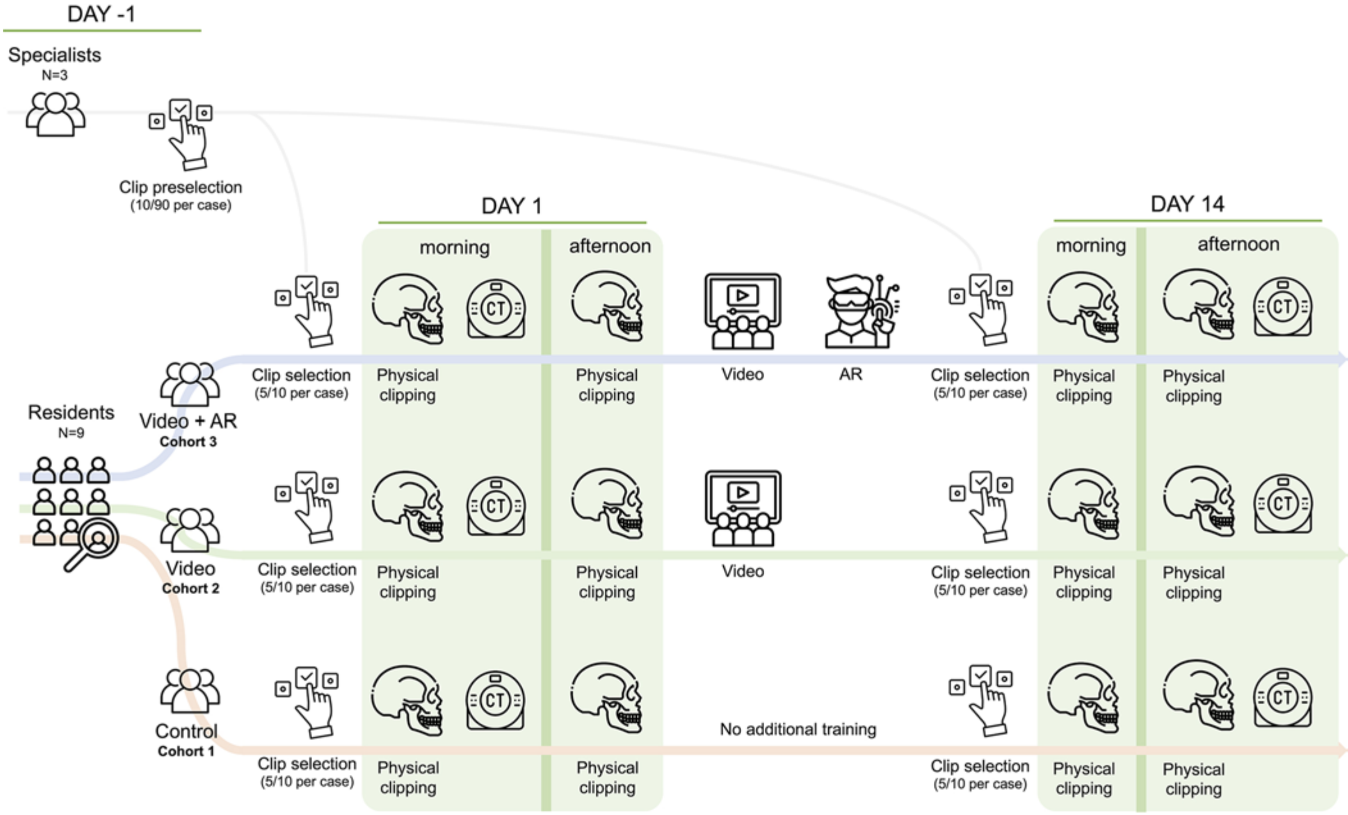

FIG. 3. Study workflow and simulation session randomization according to different levels of additional training. Before skill laboratory session days 1 and 14, the residents were required to select 5 possible clips for each aneurysm case based on the assessment of angiographic imaging data. These 5 clips per aneurysm case were chosen from a preselection of 2 suitable and 8 unsuitable clips made by 3 experts beforehand, for a total of 10 available clips per aneurysm case. Thus, the number of suitable clips (0, 1, or 2) included by the residents in their selection of 5 clips per case was measured. Residents could therefore select a maximum number of 10 correct clips among 25 selected clips in total, as each of the 9 residents completed 20 physical simulations (5 aneurysm cases per session), divided into four sessions on day 1 (sessions 1 and 2) and day 14 (sessions 3 and 4). All 9 residents of the department (PGY-1 to PGY-6) were randomly assigned by the principal investigator to three study groups exposed to different training methods between days 1 and 14: video review session alone (n = 3, cohort 2), combination of video review session and AR training (n = 3, cohort 3), and control group without interim training (n = 3, cohort 1). A stratified randomization method was applied assigning 1 PGY-1 or PGY-2, 1 PGY-3 or PGY-4, and 1 PGY-5 or PGY-6 resident per study cohort to balance the potential influence of microsurgical training levels (GraphPad online randomizer, Dotmatics Inc.).[16]

60% match during session 4, and cohort 3 (video + AR) reached a match of 73% of suitable clips in both sessions 1 and 4. However, these results did not reach statistical significance.

Aneurysm Occlusion Rate

Aneurysm occlusion of the reference sessions was assessed by ICG videoangiography and CT scans (Figs. 2 and 4). After clipping simulation sessions 1 and 4, 76% and 80% of the aneurysms were completely occluded (Raymond-Roy class 1) (Fig. 5J). Only cohort 3 (video + AR) showed a statistically significant improvement in occlusion rate between sessions 1 and 4 (p = 0.046) (Fig. 5K). The subgroup analysis of the impact of any intermittent training on the occlusion rate of pooled cohorts 2 (video) and 3 (video + AR) showed a trend toward a higher occlusion rate (p = 0.096) (Fig. 5L). Of note, the 20 insufficiently clipped cases (20/90, 22%) were attributed to inaccurate clip technique in 65% (13/20), to incorrect clip size in 25% (5/20), and to unsuitable clip-type selection in 10% (2/20). A parent artery stenosis was observed in 8 cases (8/90, 9%). Of these 8 cases, 6 were documented at the early stage of the study during session 1 (6/8, 75%).

Discussion

Introduction of a Novel Training Platform Combining Physical and Holographic Simulators

In the era of flow diversion, neurosurgeons frequently face the paradox that, even in specialized centers, the caseload of clipping procedures declines while the case complexity is simultaneously increasing.[2,20,21] Moreover, the global trend of reducing working hours for medical professionals and the growing limitations on traditional cadaveric training further add to the challenges for cerebrovascular neurosurgeons.[22] The lack of frequent hands-on microsurgical clipping experience might even compromise the maintenance of already acquired expert skills, leading to increasing demands on alternative training options.

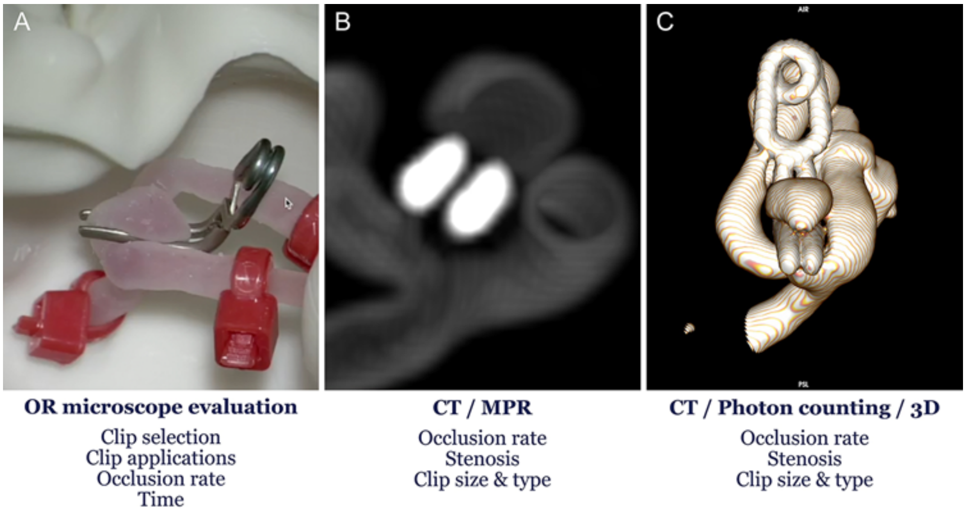

FIG. 4. Microscopic and radio-anatomical aneurysm occlusion assessment with conventional and photon-counting CT scans. **A:** The ad hoc documentation included the active simulation time of the clipping procedure, number of clipping attempts, choice of clip implant and applicator, and degree of aneurysm occlusion and parent artery patency by ICG fluoroscopy. All data were documented by two independent assessors in the laboratory and were a posteriori confirmed by revisualization of the video documentation. **B and C:** The qualitative evaluation involved the assessment of the radio-anatomical outcome and correct application of the selected clips based on standard as well as photon-counting CT scans (Siemens Emotion and Naeotom Alpha scanners). The radio-anatomical aneurysm occlusion was assessed according to the Raymond-Roy classification by two independent radiologists.[18] They investigated the final clip position in relation to the aneurysm neck on multiplanar reformatted (MPR) images (B) as well as 3D rendering (C).

So far, viable educational alternatives have included the development of simulators by using additive manufacturing techniques. Recently, virtual simulations based on virtual reality and AR have been introduced.[22–26] However, all these models do not sufficiently simulate physically realistic cerebrovascular features. In detail, vessel and aneurysm walls that are too thick lead to a consequent lack of elasticity. Previously simulated aneurysms have also been predominantly solid and thus not perfused.[27,28]

Mashiko et al. were among the first to present an enhanced but very elaborate 3D printing production process and training protocol for a hollow aneurysm model.[11,29] However, long manufacturing times and high costs have been previously identified as downsides of those experimental techniques.[11,30,31] Joseph et al. presented a simulator with a pulsatile blood-like circulation, controlled by a custom-designed pump.[13] This patient-specific simulator also demonstrated its compatibility with ICG fluorescence and was assessed in a recent questionnaire-based study.[32]

We introduce a newly developed aneurysm clipping simulator enabling patient-specific, hollow, perfused, elastic, and thus ICG-compatible aneurysm models with submillimetric aneurysm wall thickness. To our knowledge, the use of the latest generation of silicone 3D printing technology to fabricate patient-specific aneurysm models, as well as the development of exchangeable, aneurysm-comprising housings inside a prefabricated skull, has not been published before.

In addition, the material demonstrated extraordinary durability under constant perfusion, as all clipping simulations were performed on the same aneurysm models. The printed aneurysm dome thickness of less than 0.4 mm corresponded to material properties of previously published, harvested human aneurysm tissue samples. It allowed the complete apposition of the clip branches and the realistic simulation of aneurysm occlusion.[33] The durability and perfusability of the presented model enabled the conduction of a structured and objective study assessment. The ability to immediately assess aneurysm occlusion and exclude potential parent artery stenosis through ICG videoangiography is a crucial feature of the physical simulator. Furthermore, the reduced size of the exchangeable housings was identified as a prerequisite to achieve CT compatibility. In addition, the integration of AR training and the documentation of its impact on microsurgical skill development over time represent another innovation of our study. Thus, the combination of both proposed aneurysm simulators (3D printed and AR) enabled the validation of a novel cerebrovascular training platform with different levels of additional interim training.

Objective Evaluation of Our Simulator Training Program

Different assessment methods have been proposed to evaluate the impact of aneurysm simulators on both education and surgical planning.[12,34] A Japanese group presented a preclinical training program including two clipping sessions and an interim video review session, evaluated by an expert assessment based on Objective Structured Assessment of Technical Skills (OSATS).[29] Others have compared occlusion rates of novice versus experienced surgeons in preclinical settings.[31] Recently published trials of sophisticated 3D-printed clipping simulators have focused on the assessment of the phantoms' realism by conducting Likert-based questionnaires.[13,14,35]

In contrast to these previous studies, we evaluated the

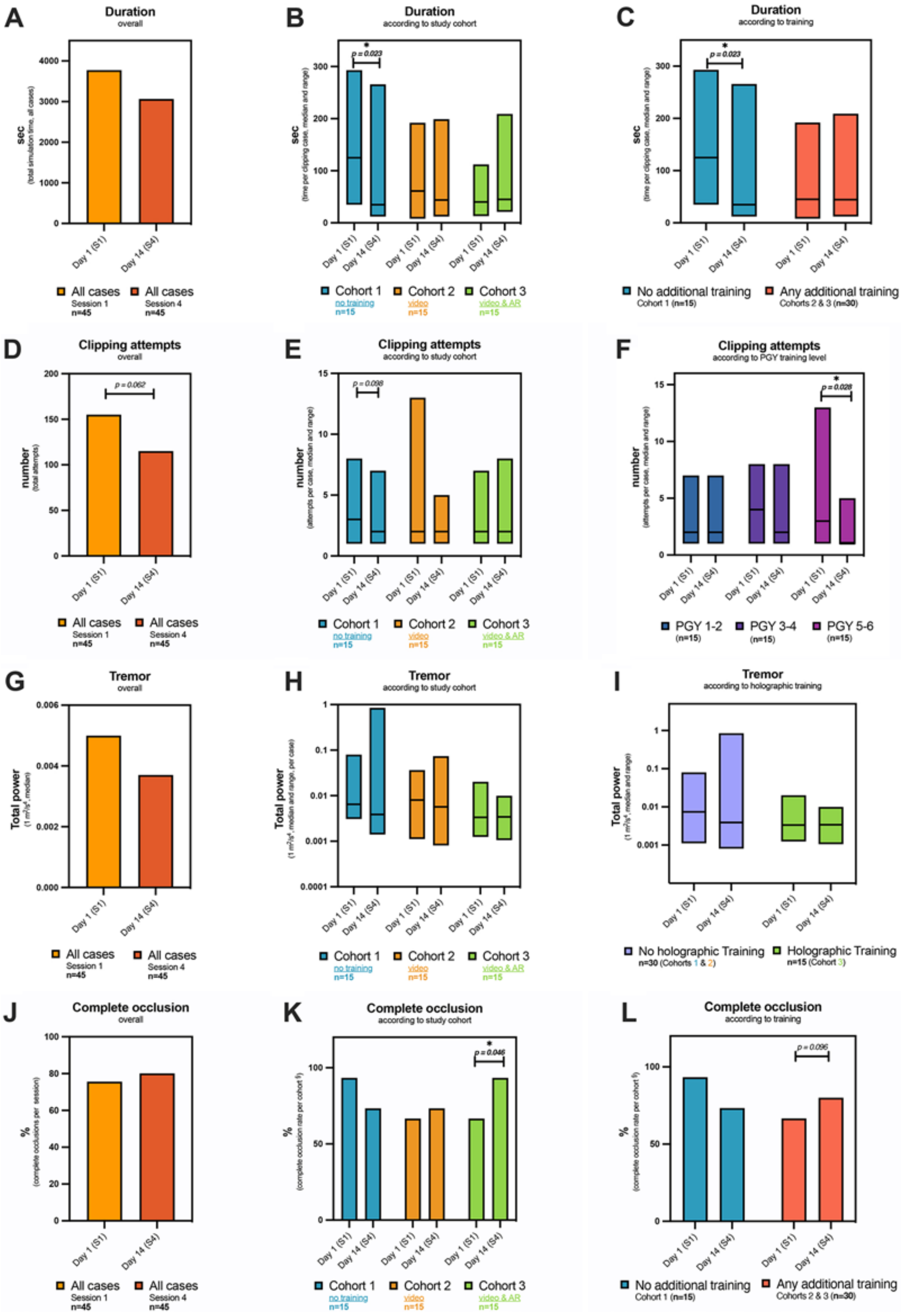

FIG. 5. Impact of simulator training on microsurgical skills. Our assessment comprised simulation durations (**A–C**) (active simulation time = chronometric measurements of clip attempts only), clipping attempts (**D–F**), wristwatch acceleration to document wrist tremor (**G–I**), and aneurysm occlusion rate (**J–L**). The overall results of reference session 1 (S1) were compared with those of reference session 4 (S4) (A, D, G, and J). Residents were randomly assigned to three cohorts and exposed to different levels of training between days 1 and 14: control group without interim training between the physical simulations (n = 3, cohort 1), video review session alone (n = 3, cohort 2), and combination of video review session and AR training (n = 3, cohort 3). Further comparisons between these training cohorts (B, E, H, and K) or between pooled cohorts (C, I, and L) assessed the impact of additional training on the improvement of microsurgical skills. Moreover, the impact of simulator training on different microsurgical training levels was evaluated (F). *$p < 0.05$.

TABLE 1. Overview of results of sessions 1 (day 1) and 4 (day 14)

	Day 1/Session 1	Day 14/Session 4	p Value
Physical clipping simulations			
Cohort 1	15	15	
Cohort 2	15	15	
Cohort 3	15	15	
Duration of physical simulation, sec	3776	3065	0.190
Duration of physical simulation per case, sec			
All cohorts	70 (8–293)	43 (12–266)	0.190
Cohort 1	125 (35–293)	35 (12–266)	**0.023**
Cohort 2	61 (8–192)	44 (12–199)	0.955
Cohort 3	40 (13–112)	45 (21–209)	0.755
Total no. of clipping attempts			
All cohorts	155	115	0.062
Cohort 1	63 (41)	42 (37)	0.098
Cohort 2	56 (36)	38 (33)	0.162
Cohort 3	36 (23)	35 (30)	0.823
PGY-1 or PGY-2	43 (28)	42 (37)	0.975
PGY-3 or PGY-4	55 (35)	44 (38)	0.405
PGY-5 or PGY-6	57 (37)	29 (25)	**0.028**
Total power of wrist tremor, m^2/sec^4			
All cohorts	0.0050 (0.0011–0.800)	0.0037 (0.0008–0.8480)	0.333
Cohort 1	0.0065 (0.0031–0.0800)	0.0039 (0.0014–0.8480)	0.460
Cohort 2	0.0080 (0.0011–0.0363)	0.0057 (0.0008–0.0741)	0.683
Cohort 3	0.0033 (0.0012–0.0202)	0.0034 (0.0011–0.0100)	>0.999
PGY-1 or PGY-2	0.0049 (0.0011–0.0093)	0.0035 (0.0008–0.8480)	0.638
PGY-3 or PGY-4	0.0050 (0.0024–0.0513)	0.0074 (0.0011–0.0885)	0.363
PGY-5 or PGY-6	0.0074 (0.0012–0.0800)	0.0036 (0.0011–0.0104)	**0.027**
Complete aneurysm occlusion			
All cohorts	34/45 (76)	36/45 (80)	0.593
Cohort 1	14/15 (93)	11/15 (73)	0.180
Cohort 2	10/15 (67)	11/15 (73)	0.655
Cohort 3	10/15 (67)	14/15 (93)	**0.046**

Values are given as number (%) or median (range) unless otherwise indicated. Boldface type indicates statistical significance. Wilcoxon signed-rank tests for paired samples were used to compare metric or ordinal data of sessions 1–4. Cohort 1 received no interim training, cohort 2 received a video review session, and cohort 3 received a video review session and holographic clip simulation training between sessions 2 and 3.

training effect of our physical aneurysm simulator in a randomized controlled study and introduced three different levels of training.[13,14] All study participants performed physical clipping simulations distributed over two sessions on day 1 and two sessions on day 14 in a realistic, microsurgical scenario. In between the simulated clipping sessions, we subjected the residents to no additional interim training, a video review session alone, or a combination of video review session and AR training.

The AR head-mounted HoloLens system has been recently used as an adjunctive tool to visualize neuroanatomy and treatment plans, or as a mixed reality tool inside the operating room for the visualization, but not active simulation, of different aneurysm clipping strategies.[36,37] To date, no randomized controlled trial has assessed the combined use of physical aneurysm phantoms with AR training. For our study, a holographic application for the HoloLens 1 was developed with the aim to visualize perianeurysm anatomy and to train virtual clipping applications on the matching physical aneurysm cases. Finally, conventional and photon-counting CT scans, ICG, and a smartwatch were introduced to objectively assess microsurgical skills and aneurysm occlusion rates.

Simulator Training Improves Microsurgical Skills and Aneurysm Occlusion Rates

So far, data regarding the use of modern aneurysm simulators in combination with objective performance metrics are scarce.[13,14,29,38] In the field of 3D-printed aneurysm simulation, our study's combination of objective assessment parameters, radiological aneurysm occlusion rates, clipping attempts, implant choices, surgical tool movement metrics, and active simulation times is unprecedented.

Overall, our results confirmed the positive effects of repetitive training sessions and demonstrated improved microsurgical skills. Furthermore, the impact of additional training modalities on the residents' performance became evident. In detail, simulation time improved by 39% for all participants throughout the study. Although limited by the small cohort sizes, the effect of repetitive physical training alone showed a significant improvement in the group that did not receive additional interim training. The lack of significant improvement of the remaining cohorts with additional interim training (cohorts 2 and 3) could be explained by the potential bias that both cohorts had already demonstrated excellent results at baseline. Only one previous study by Mashiko et al. presented comparable time measurements in a resident trial setting.[29] The simulation time of all six trainees improved, but in contrast to our study, their measurement referred to the phase from dural incision to detection of the aneurysm neck only.[29]

Recent studies have highlighted a growing demand for objective training assessment.[39] Ahmed et al. presented a questionnaire-based study intended to validate a synthetic simulator.[14] Novice and expert study participants were required to wear force-sensitive gloves, allowing the evaluation of force applied by the dominant thumb to the applicator between both groups.[14,39]

We introduced surgical tool movement metrics to better visualize the impact of repetitive physical simulation training and additional interim training on the residents' performance. To the best of our knowledge, wrist tremor measurements, as an indicator of surgical confidence, have not been used to monitor neurosurgeons-in-training before. Our smartwatch accelerometer measurements revealed an overall improvement of 26% between the first and last reference sessions. Interestingly, the more experienced residents (PGY-5 and PGY-6) tended to have more kinematic movements and clipping attempts during the first session than their juniors. This might be potentially influenced by being too eager to achieve a complete aneurysm occlusion. However, the significant improvement of kinematics and clipping attempts among senior residents demonstrated the value of skill laboratory training and its impact on surgical confidence even for experienced neurosurgeons.[40]

Different study groups assessed their simulators' efficacy by clinical application aiming to predict suitable clips ahead of the actual microsurgical procedure. In these cases, the rate of implant accordance, surgical complications, and procedural duration were reported to document trainees' performance.[30,34,41] Kimura et al. proposed assessing the position of the clip and its neck coverage by an endoscope in the 3D-printed surgical situs.[41] Futami et al. demonstrated the importance of CTA scans to assess aneurysm neck coverage after clipping as early as 2004.[42] Others have shown artifact reduction capabilities of photon-counting CT scans after endovascular aneurysm treatment.[43]

To date, no previous clipping simulation study has combined ad hoc ICG videoangiography and post hoc radio-anatomical evaluation of aneurysm occlusion rates as performed in our study. Thus, we could show that physical clipping simulation training in combination with additional training (video review session and AR training) achieved a marked improvement in radio-anatomical occlusion rates and clipping attempts. Of note, among experienced PGY-5 and PGY-6 residents, the physical simulation training alone, irrespective of additional interim training, led to a significant reduction in the number of clipping attempts, indicating improved microsurgical skills and confidence.

Limitations

Our limitations include the center-based nature and small sample of the study. Despite the low number of participants, the many repetitions and hours spent in the skill laboratory by the residents were sufficient to demonstrate trends, even significant improvements of their microsurgical skills and occlusion rates. Because of the tight time schedule of the 36 sessions and the limited availability of CT scanning times outside clinical routine, we had to focus our evaluation on the 90 reference simulations. The simulation experience was limited to the training of clip selection, application, and microsurgical skills. The equally important steps of craniotomy and sylvian and peri-aneurysm dissection have not yet been simulated and will be included in future studies.

Furthermore, we did not document any intraoperative aneurysm ruptures. While this demonstrates the durability of the printed models, further technological improvements will be necessary to facilitate the establishment of a controlled, rupture-prone model and the reproduction of inhomogeneous wall properties and wall thicknesses, small blebs, or calcifications. Finally, the AR training was provided on a previous generation of the HoloLens platform. We expect a marked improvement of the graphic interface and system stability in the latest HoloLens 2 generation.

Conclusions

This study presents the first preclinical results validating newly developed physical and holographic aneurysm clipping simulators. It represents the largest randomized controlled series to date to evaluate patient-specific, perfused, and elastic aneurysm models with submillimetric aneurysm wall thickness. The development of exchangeable, aneurysm-comprising housings allows objective radio-anatomical evaluation through conventional and photon-counting CT scans. Our training model includes several measurable performance metrics that may objectively document improvements in microsurgical skills and surgical confidence. Moreover, the different training levels of our novel simulator platform enable a training program tailored to the level of experience and needs of the cerebrovascular trainees.

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Disclosures

Dr. Dodier, Mr. Königshofer, Mr. Civilla, and Dr. Moscato reported a patent pending (102023000010689). Dr. Redaelli reported a patent pending (I0202616).

Author Contributions

Conception and design: Dodier, Civilla, Haider, Cho, Wang, Unger, Redaelli, Moscato. Acquisition of data: Dodier, Civilla, Mallouhi, Lederer, Wang, Dorfer, Hosmann, Unger. Analysis and interpretation of data: Dodier, Civilla, Mallouhi, Haider, Cho, Rössler, Unger, Frischer, Moscato. Drafting the article: Dodier, Mallouhi, Haider, Frischer. Critically revising the article: Dodier, Civilla, Mallouhi, Haider, Cho, Lederer, Dorfer, Hosmann, Rössler, Redaelli, Frischer, Moscato. Reviewed submitted version of manuscript: Dodier, Civilla, Mallouhi, Cho, Wang, Dorfer, Hosmann, Frischer, Moscato. Approved the final version of the manuscript on behalf of all authors: Dodier. Statistical analysis: Dodier, Civilla, Frischer, Moscato. Administrative/technical/material support: Dodier, Civilla, Mallouhi, Lederer, Wang, Rössler, Königshofer, Unger, Moscato. Study supervision: Dodier, Rössler, Palumbo, Moscato.

Supplemental Information

Videos

Video 1. https://vimeo.com/880243409.
Video 2. https://vimeo.com/880245758.

Online-Only Content

Supplemental material is available online.

Table S1. https://thejns.org/doi/suppl/10.3171/2023.10.FOCUS23640.

Previous Presentations

Preliminary data were presented at the 58th Annual Meeting of the Austrian Neurosurgical Society (ÖGNC 2022), Vienna, Austria, October 1, 2022; Vienna Center for Engineering Medicine Biennial ViCEM Meeting, Austrian Chapter Meeting of the European Society of Biomechanics, Vienna, Austria, September 23, 2022; Additive Manufacturing in Medicine 4th Symposium (M3D+it 2022), Vienna, Austria, December 3, 2022; and Symposium on Cerebrovascular Surgery and Intervention, Vienna, Austria, May 27, 2023.

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