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The role of high-fidelity simulation in the acquisition of endovascular surgical skills: A systematic review.

Abstract

Introduction

The widespread introduction of minimally invasive endovascular techniques in cardiovascular surgery has necessitated a transition in the psychomotor skillset of trainees and surgeons. Simulation has previously been used in surgical training; however, there is limited high quality evidence regarding the role of simulation-based training on the acquisition of endovascular skills.

This systematic review aimed to systematically appraise the currently available evidence regarding endovascular high-fidelity simulation interventions, to describe the overarching strategies used, the learning outcomes addressed, the choice of assessment methodology, and the impact of education on learner performance.

Methods

A comprehensive literature review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement using relevant keywords to identify studies evaluating simulation in the acquisition of endovascular surgical skills. References of review articles were screened for additional studies.

Results

A total of 1081 studies were identified (474 after removal of duplicates). There was marked heterogeneity in methodologies and reporting of outcomes. Quantitative analysis was deemed inappropriate due to the risk of serious confounding and bias. Instead, a descriptive synthesis was performed, summarising key findings and quality components. Eighteen studies were included in the synthesis (15 observational, 2 case-control and 1 randomised control studies). Most studies measured procedure time, contrast usage, and fluoroscopy time. Other metrics were recorded to a lesser extent. Significant reductions were noted in both procedure and fluoroscopy times with the introduction of simulation-based endovascular training.

Conclusion

The evidence regarding the use of high-fidelity simulation in endovascular training is very heterogeneous. The current literature suggests simulation-based training leads to improvements in performance, mostly in terms of procedure and fluoroscopy time. High-quality randomised control trials are needed to establish the clinical benefits of simulation training, sustainability of improvements, transferability of skills and its cost-effectiveness.

1 Introduction

In recent years, vascular surgery has seen the introduction of several endovascular techniques. This has resulted in a paradigm shift with increasing evidence supporting the usage of endovascular techniques for the treatment of aneurysmal disease, peripheral arterial disease, and venous pathologies.[1-3] This shift has been accompanied by a multitude of challenges and changes in training healthcare professionals.[4] Endovascular technologies have necessitated a transition in the psychomotor skillset of trainees and established surgeons, as they adapt to entirely new modes of practice. This is further compounded by rapid technological innovations and constant introduction of new devices.[5]

The aim of specialist vascular surgical training programmes is to produce surgeons capable of independent practice in open and interventional techniques.[6] Internationally, the training and education of vascular surgeons on the constantly evolving and ever growing endovascular techniques is crucial for their continuing professional development. However, within the United Kingdom, vascular trainees within these programmes are recognised to be the most dissatisfied trainees.[7, 8] Reasons include an imbalance between training time and service provision; [9] limited surgical experience; [6, 10] and the loss of the ‘firm structure’ associated with the transition to shift systems.[6] A recent report showed that up to 78% of trainees spent no time in theatre or performing core surgical skills during their most recent workday, and between 78% and 95% spent no time receiving any formal operative teaching.[8] This lack of case-volume experience has important implications for patients.[11] Similar experiences have been reported in the United States where access to specialised care has languished with opportunities for specialty training in vascular medicine remain limited. In their recent review, Eberhardt et al. highlight that inadequate funding and under-recognition by accreditation and certification bodies are the primary driving forces for limited access to training within vascular medicine.[12] The situation only worsened in light of the COVID-19 pandemic, with significant reduction in operative experience necessitating extension to training for many trainees in order to meet the required level of competence.[13] The requirement to obtain specific operative competencies within a restricted and curtailed training period has left trainees and educators seeking novel and innovative methods to gain competence and confidence within their training programmes.[14]

High-fidelity simulation is a form of simulation training that provides the learner with an environment which offers a significant degree of realism and believability to the teaching experience through the combined utilisation of: equipment, setting, scenario and personnel.[15-18] It presents an opportunity for developing experience and competence in a wide-range of procedures within a safe space.[19, 20] The simulated environment acts as a medium for structured mentoring with the added benefit of learning from mistakes, which entirely mitigates against the risk of patient injury and the medicolegal liability.[21] Table I summarises the different types of simulation modalities utilised for acquisition of procedural skills alongside their advantages and disadvantages. Given that most endovascular technologies were adopted in first-line clinical practice only in recent years, there is uncertainty of the value of simulation-based training in gaining endovascular skills.

This systematic review aims to appraise the currently available evidence regarding endovascular simulation interventions, to describe the overarching strategies used, the learning outcomes addressed, the choice of assessment methodology, and the impact of education on learner performance.

2 Material and Methods

This review was not suited to one single research paradigm and therefore both constructivism and positivism methodology were employed. Positivism was used to describe and justify the educational interventions and associated assessments to confirm effectiveness and define pedagogy.[22] A constructivist approach was also implemented, through clarification of the underpinning theoretical frameworks that inform education and assessment methodology.[23] By adopting a contextual realism ontological approach, our review allows us to present a description of which endovascular simulation interventions work, and in what specific educational contexts, which is an appropriate approach in a field contaminated by educational and methodological heterogeneity.[22] The manuscript was reported in accordance with the STORIES statement; a publication standard for healthcare education evidence synthesis.[24]

2.1 Search Strategy

An initial scoping search was conducted to identify and refine the search syntaxes and to establish the relevant inclusion and exclusion criteria. A study protocol was designed which involved a multi-investigator search strategy and document retrieval process. A comprehensive literature review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement using relevant keywords.[25] The specific endovascular techniques and procedures eligible for inclusion were chosen through consensus, and represent the most performed endovascular procedures, in which competency would be expected by the end of vascular surgical training in the UK (Table II). This review embraced all study designs which utilised high-fidelity endovascular immersive extended-reality simulators i.e. virtual reality, augmented reality, and mixed reality as an education intervention with the aim of improving technical skill in relation to pre-specified endovascular procedures. For inclusion, studies needed to describe both baseline and post-intervention performance metrics, to allow for the measurement of change resulting from the educational intervention. Studies embracing medical students, surgical trainees, and consultant surgeons or interventionalists were eligible for inclusion. Research describing outcomes at all levels of Kirkpatrick's hierarchy were eligible for inclusion.[26]

With the aid of a clinical librarian, the following online databases were searched from inception date of database up to June 2022 using a standardised search strategy: EMBASE, MEDLINE, Google Scholar, Cochrane, and AMED. Abstracts available from relevant education and vascular surgery societies, including the Association for Medical Education in Europe (AMEE), Association for the Study of Medical Education (ASME), Society for Vascular Surgery (SVS), Association of Surgeons in Training (ASiT) and The Royal College of Surgeons were also searched for the last 6 meetings to ensure any study currently under review, but not fully published, were included. The reference lists of the studies meeting the inclusion criteria were hand-searched for additional relevant studies, as were previous systematic reviews reporting on endovascular simulation, as identified through the scoping searches. [27, 28] The search syntaxes and an example search strategy are presented in Table III.

2.2 Data extraction and quality assessment

Titles of the studies yielded from the search strategy were reviewed by AG and CGC. Of those titles with potential relevance to the research question, the abstracts were independently screened by AG and CGC using an abstract screening tool (Appendix A). Any study passing the abstract screening process proceeded to full-text eligibility assessment, in which AG and CGC independently and blindly validated studies against a full manuscript screening tool (Appendix B). Disputes at the abstract screening stage and full-text eligibility assessment stage were resolved by consensus between AG and CGC.

A data extraction form was developed which included a research quality assessment tool, utilising guidance from Best Evidence Medical Education, PRISMA and Reed et al. (Appendix C and D). [29-31] The components of the quality assessment were: backgrounds and objectives, research design, education intervention, assessment, results and conclusions, and impact. Each quality item was further classified as assessing research methodology quality or reporting quality. The research methodology quality assessment was completed as a ‘yes/no’ response to six questions focusing on describing the evidence-base, defining the study objectives, executing an appropriate study design, implementation of control groups, evidence of randomisation, and appropriate use of statistical tests. The reporting quality assessment involved twelve items, which included three ‘yes/no’ items reporting on the study design, learner characteristics and matching of outcomes to objectives. Eight reporting quality indicators were scored on a three-point Likert scale, and included: description of the educational intervention, process and outcome of assessment, educational context, and resources utilised; discussion of theoretical models underpinning both the choice of intervention and assessment; details of the application of psychometrics to assessment; and the provision of materials to allow for assessment replication. The educational impact of interventions were classified in accordance with Kirkpatrick's adapted hierarchy,[32] in-line with guidance provided by Best Evidence Medical and Health Professional Education (BEME).[29]

2.3 Data analysis

The initial scoping search revealed a significant degree of heterogeneity in methodology and reporting outcomes. The relevant data, results and conclusions were extracted and collated manually from the studies using the electronic data extraction form.

Quantitative analysis was deemed inappropriate due to the risk of serious confounding and bias. Instead, a descriptive synthesis of these studies was performed, summarising key findings and quality components.

3 Results

3.1 Search results

We identified 474 records following initial searching of the databases and alternative sources and following removal of duplicate results. After applying our eligibility criteria, title and abstract screening, and final full-text review, 18 studies met our criteria for inclusion in this review.[5, 33-49] The PRISMA flow diagram detailing study selection is shown in Figure 1. Agreement between the two reviewers at the full text-eligibility assessment was good (kappa statistic: 0.90). An overview of the included papers is presented in Table II. Data were extracted by AG and CGC, who achieved concordance in 92% of quality ratings.

3.2 Study participants and design

Table IV summarises the key information points from the included studies such as: demographics, study design, simulation intervention, assessment tool and results of the eighteen included studies.

Of the eighteen studies, nine were based in the United States,[33-36, 42, 43, 45-47] seven in the United Kingdom,[5, 37, 38, 40, 44, 48, 49] and two in Italy.[39, 41] The mean number of participants per study was 21 (range: 5 – 100, median: 15, pooled total: 378) in the eighteen included studies. The participants varied broadly in speciality and stage of training. The most frequent participating groups were defined as: vascular surgery trainees / residents (in six (33.3%) studies), radiology trainees / residents (in four (22.2%) studies), general surgery trainees / residents (in four (22.2%) studies), medical students (in four (22.2%) studies), and experienced endovascular surgeons and interventionalists (in seven (38.9%) studies). Fifteen of the included studies were observational studies,[5, 33, 35-38, 40-47, 49] with two case-control studies [34, 39] and a single randomised control study.[48]

3.3 Quality assessment

A standardised rigorous quality assessment of the final selection of studies was conducted jointly by both AG and CGC, summarised in table V.

Many of the studies included were deemed to be of poor to moderate quality. They were found to be lacking in key areas such as: research design (most notably lack of randomisation and use of a control group), description of theoretical principles that underpin the choice of both educational intervention and assessment. The studies were quality assessed using a standardised nineteen-point scale. The scores ranged from 26% to 79% (mean: 61%, mode: 63%, median 63%, s.d. 13%).

While all studies provided a broad and selective description of the literature, none demonstrated a systematic approach in appraising the evidence-base. Thirteen of the 18 provided a clearly defined and well-described objective to the study.[5, 33, 35, 37-40, 43-45, 47-49] In terms of research design, all studies adopted an appropriate study design to answer the given research questions. Six studies explicitly stated the study design within the published manuscript;[34, 39, 43, 44, 48, 49] the remaining 12, failed to do so. Two studies utilised a control group, with both implementing a randomisation process for cohort allocation.[34, 39] Eight of the included studies provide details on the learner characteristics.[5, 34, 39, 40, 43, 47-49] While the educational intervention was described in all 18 studies, only ten described it in appropriate detail as to facilitate replication.[5, 34-36, 39, 40, 43, 47-49] Of the 18 studies, six studies provide details relating to the tools and resources required to deliver the educational intervention in enough detail as to facilitate replication.[33, 34, 36, 47-49] 16 studies fail to describe any theoretical models or conceptual frameworks underpinning the choice of educational intervention, with the remaining two studies providing a limited description.[5, 40] 16 studies provide a clear description of the process and outcome the assessment, with the remaining two providing a limited description.[42, 44] Eleven studies fail to provide any discussion on theoretical models or conceptual frameworks underpinning the specific choice of assessment, [33, 34, 36-38, 41, 42, 44, 45, 47, 48] with a further five providing a limited description.[5, 35, 39, 46, 49] Of the 18 studies, the educational context of the assessment was clearly described in two of them,[43, 46] with 14 studies failing to provide any detail in this area.[34-40, 42, 44, 45, 47-49] Eleven studies provided clear and in-depth information on the materials required to facilitate replication of the assessment process.[5, 34, 35, 38-41, 43, 46, 47, 49] The limitations of the research conducted is clearly described in four studies,[35, 37, 40, 46] with three studies failing to recognise any limitations in the research methodology.[33, 34, 42] The outcomes of all 18 studies were the modification of knowledge and skill, sitting at Kirkpatrick's level 2b.[26]

3.4 Educational intervention

The emphasis on simulation within the education interventions varied widely amongst the included studies. The intensity of education varied from an isolated 30–60-minute session to performing 72 simulations over the course of months.[34, 45] A range of simulators were used, including the Mentice VIST simulator (n = 9) and the

Simbionix Angio Mentor simulator (n = 7). In most studies, simulation was the main tool of intervention (n = 16), with only four studies incorporating other educational methods, such as didactic teaching, computer-based training and tabletop procedure demonstrations.[33, 43, 47, 49] The included studies in this review simulated different endovascular procedures as part of the simulation training interventions. The endovascular procedures simulated include: carotid artery stenosis stenting, renal artery angiography and angioplasty, thoracic endovascular aortic repair, IVC filter placement, and infra-renal EVAR. Only four studies directly report utilisation of expert tutor feedback and guidance during the educational components of the programmes (excluding the assessment stages).[5, 36, 41, 43] The remainder utilised repetition and simulator-reported outcomes to guide learning, rather than expert mentoring supporting the use of the simulator.

3.5 Assessment of educational intervention

All 18 studies utilised simulator-reported outcomes as a tool to monitor response to the interventions.[5, 33-49] Common outcomes include total procedure time, total volume of contrast used, fluoroscopy time and the number of catheters required. The more advanced simulators reported variables such as percent of residual stenosis, placement accuracy, error frequency and catheter movements. All studies utilised the first or second, and last simulation to evaluate performance. Several studies, in addition to the simulator-reported metrics, used instructor evaluation to monitor participant technical ability improvement.[35, 36, 49] For example, Dayal *et al* scored participants out of five for catheter manipulation technique, guidewire manipulation technique, catheter exchange technique and monorail technique.[36] Seven studies also opted for subjective performance assessment by an expert instructor using Likert-scale assessment tools.[5, 35, 40, 42, 43, 46, 49]

3.6 Learning outcomes

The most reported objective measures were total procedure time (18 studies)[5, 33-49], total fluoroscopy time (16 studies)[33-40, 42-49] and total volume of contrast used (13 studies)[33-41, 43, 46-49].

In all the 18 included studies with the aid of the varying educational interventions, a significant improvement was noted in total procedure time with p-values ranging from 0.001 to 0.05 signifying the degree of significance.[5, 33-49]

Total fluoroscopy time was measured in 16 of the included studies out of which significant improvements were found in 12 studies with p-values ranging from 0.005 to 0.05 signifying the degree of significance.[33, 35-37, 39, 40, 43-47, 49] The four studies which showed a lack of significant difference in fluoroscopy time did not share any overlap within the educational intervention they implemented.[34, 38, 42, 48] The number of participants within these studies ranged from 5 to 29 and the degree of exposure to the simulator ranged from a single 30–60-minute protracted sessions through to 20 repetitions of 3 different procedures.

Total contrast volume was measured in thirteen of the included 18 studies. [33-41, 43, 46-48] Six studies demonstrated a significant reduction in volume of contrast used throughout the simulation with p-values ranging from 0.001 to 0.05 signifying the degree of significance.[33, 36, 38-41, 49] The seven studies which showed a lack of significant difference in volume of contrast used varying educational interventions that ranged from a single 30–60-minute protracted sessions through to completing an eight-week course.[34, 35, 37, 43, 46-48] The number of participants within these studies ranged from 12 to 41 and there was no overlap in the educational intervention being implemented.

Of the 18 studies, only four demonstrated significant improvements in the 3 most reported measured outcomes i.e. total procedure time, total contrast volume and fluoroscopy time.[33, 36, 39, 40] They were all relatively small studies with participant count ranging from 9 to 21 participants. There was no heterogeneity in the choice of educational intervention each with a unique approach ranging from two-hour personalised tuition through to a two-week longitudinal course. The experience of the participants greatly varied which included some medical students through to vascular surgeons with significant prior experience. Of these four studies, two utilised the VIST simulator whilst the other two used the SimSuite simulator and the Angio Mentor Dual-Sim simulator. All four studies conclude that more junior-level participants stand to make the most significant improvements in all three metrics.

4 Discussion

Simulation within vascular and endovascular surgery is constantly evolving field. Advancements in technology are increasingly being incorporated into training programs. Simulators, augmented reality, mixed reality, and artificial intelligence algorithms are becoming more widely used within educational interventions in vascular surgery to provide tailored training programs. These technologies especially ones utilising mixed reality have the potential to be deployed in operating rooms to monitor the surgeon's movements, ergonomics to better assess, monitor and improve surgical skills and learning curves.

This systematic review focussed on examining the role of high-fidelity simulation in the acquisition of endovascular surgical skills by looking at both objective and subjective performance metrics.

Whilst there was significant heterogeneity in the methodology of the included studies regarding the simulation programs as well as endovascular procedures used, they all demonstrated significant improvements in simulator procedure time following the use of a simulator. Twelve studies demonstrated significant improvements in fluoroscopy time.[33, 35-37, 39, 40, 43-47, 49] Six studies demonstrated significant improvements in the total volume of contrast used. [33, 36, 38-41] Only four studies demonstrated significant improvements in all three of the aforementioned parameters.[33, 36, 39, 40]

There were significant disparities between the included studies in the nature and design of the educational intervention used as the choice as well as the number of participants included which ranged from 5 to 100 (mean: 21, mode: 20, median 15).

All studies recorded and reported objective outcomes, whereas subjective outcomes were measured in only nine studies. There was marked variability in the outcomes measured across the included studies.

With regards to assessment, nine studies utilised a variety of subjective assessment scales for measuring trainee performance. An overwhelming majority of studies used non-validated scoring systems which had inbuilt inherent biases from non-blinded assessors. In all nine of these studies, significant improvements in subjective scores were noted in the novice groups in keeping with the objective scores discussed earlier. When assessing the more experienced expert operators, three studies found no significant differences in the recorded subjective scores.[35, 36, 46] This highlights that junior trainees are most likely to make significant progress and improvements when assessed subjectively by experts, in keeping with the objective measures recorded using the simulator.

The studies we reviewed highlight the advantages of high-fidelity simulator-based training in conjunction with clear objectives utilising an experienced tutor for formative feedback. This is important in developing the psychomotor skills of aspiring vascular surgeons and interventionists; especially in the more junior trainees when combining the impacts of both objective and subjective scores.

Van Herzeele et al. explored whether innate perceptual, visuospatial, and psychomotor aptitude (VSA) can predict the acquisition of technical skills needed for endovascular surgery.[40] They noted that the most dextrous students had the innate ability to utilise the simulator to a greater extent on their first endovascular attempt through gentler and steadier handling of the instruments as well as reduced fluoroscopy times. Interestingly, they hypothesised that could be linked to a stronger ability to recall visual images which was proved through a strong correlation between Rey-Osterrieth Complex Figure (ROCF) test scores and fluoroscopy times. They also noted that a ROCF scores were predictive of initial and end VR simulator performance and may have a role in trainee selection as well as creating tailored training programs and resources to meet the individual needs of the trainee.

Klass et al. noted that trainees would make considerable early improvements in their performance with repeated attempts prior to plateauing.[44] On analysis of operator mistakes they noted that the frequency remained constant which was believed to likely be due to the fact that trainees were learning in a safe environment which allowed and encouraged participants to experiment and explore new techniques.

To move away from the traditional apprenticeship method of training, simulation-based training can be used to shift to the modern competency-based style training achieved through meeting established "lab benchmarks".[39, 40, 50, 51] Several recommendations have been proposed as to how simulation training can be best utilised. Hsu et al. have recommended that training programs should consist of a combination of both didactic and patient-based simulation teaching by an experienced proctor.[34] Aggarwal et al. recommended a graded approach as part of a structured curriculum mixed with didactic learning aiming for competency-based training.[38] Kendrick et al. postulated that performance gains could be further maximised through the use of simulation when targeted specifically towards procedures in which adequate trainee exposure is difficult or problematic.[46] Mazzaccaro et al. stated that it is beneficial to simulate harder cases for both trainees and experts to practice, however; they noted that simulation of difficult cases lacked the same improvements in the learning curve compared to the easier simulations.[41]

There were multiple limitations in the studies included in this systematic review that we have identified. Only a small number explicitly stated their study design. Furthermore, only two of the included studies were randomised studies. A limited number of objective simulator metrics were recorded which also varied between different studies. Procedure time was the only parameter recorded in all studies. Other parameters such as total contrast volume and total fluoroscopy time were recorded in most of the studies. Kim et al focused only on one aspect of the procedure (stent placement) rather than the entire procedure.[45] Several earlier studies have commented on lack of objective metrics being a limiting factor. This appears to have been rectified in the more recent studies which utilised newer models of the simulators. Most of the included studies had a small sample size with only 4 studies having more than 20 participants. Furthermore, there was significant heterogeneity amongst the participants’ experience. The study by Lee et al was the only one to utilise a validated global assessment scale.[43] Stand-alone subjective assessment was susceptible to bias from non-blinded assessors or self-assessments. In combination with objective simulator metrics, it was deemed as a reliable measure of progress.

The studies we reviewed demonstrated that use of a simulator had led to improvements in both objective and subjective metrics; most notably in novice trainees. However, there were significant variations in the educational interventions applied by all of the studies we reviewed with regards to their structure and duration of time spent on the simulation. In light of this, additional confounding variables that may explain these improvements were not identified nor limited; such as: repeating the same simulation scenario which gives rise to the concept of "negative training", the varying degrees of mentorship within the different interventions, prolonged time interval between attempts which allows for real-life experience gained in the interim to impact performance.

One of the challenges of incorporating simulation-based training is the difficulty in establishing proficiency in a procedure or simulation scenario. A recent study by Moglia et al. described a novel protocol for defining proficiency in three simulated cases by analysing the VR simulator metrics of expert surgeons; using this as a first step towards a creating a standardised competency-based curriculum on fundamental endovascular skills.[52] In 2016, Maertens et al. developed and validated a structured, stepwise, proficiency-based endovascular program to train cognitive, technical, and human factor skills.[53] The group successfully demonstrated the efficacy of this proficiency-based approach, but highlighted significant hurdles to its integration within daily practice.[54]

Some of the studies reported limitations with the simulators used. Older models lacked realistic haptics as well as suffered with both software and hardware malfunctions. They also lacked the ability to import patient specific data/CT imaging; which is now possible with newer models. Additionally, simulators fail to assess finer technical aspects such as economy of movement or damage to surrounding tissue which necessitates the presence of an experienced mentor at hand to give constructive feedback. Moreover, simulators omit several key procedural steps such as accessing the desired entry point (which could also be simulated using ultrasound-guided puncture) and vessels as well as the inability to simulate both expected and unexpected complications encountered. Simulations are also limited by their inability to fully mimic reality with all the other environmental factors and pressures typically encountered in the operating theatre. This issue was highlighted by Bakhsh et al during their prospective study, during which they identified measurable increase in stress amongst surgeons during high-fidelity endovascular simulation with impact on performance. They also concluded that there is a role for high-fidelity team simulation in improving non-technical skill, reducing intraoperative stress, and reducing errors.[55] Several studies noted that simulator performance and metrics lacked the ability to discern subtle differences between levels of skills/experience.

Simulator performance alone does not model the true success of interventional procedure nor do time measures indicate proficiency in a specific procedure; which are seen as secondary measures. A better primary measure of assessing true success would be: the quality of the diagnostic images, the clinical outcome of the therapeutic intervention, and the experience of the patient.

Establishing and maintaining a simulation facility is very costly at present due to the nature of the specialist simulators and personnel skillset needed. The costs have been estimated to range from £12,000 to £185,000 (14, 24, 30). As a result, they are only available in select few locations. However, it has been suggested that training using a simulation-based curriculum can be less expensive than training within a hybrid angiosuite.[56]

This review sought to include all studies utilising endovascular immersive extended-reality simulators such as virtual, augmented, and mixed reality simulators. However, only studies which used virtual reality simulators matched our inclusion criteria. Consequently, we were unable to assess the role of the other types of simulators. However, the field of immersive extended-reality simulators is rapidly expanding showing plenty of promise for further enhancing the fidelity of simulation for endovascular surgeons.

Further research is needed to establish the duration of performance gains via the simulator as well as extent of transferability of skills acquired into performance within the operating theatre. Furthermore, additional research is needed to determine the link between psychomotor, visuospatial abilities and simulator performance as well as the optimum amount of time and routine that should be spent on the simulator using long term longitudinal follow up.

5 Conclusion

The use of high-fidelity simulation leads to improvements in simulator performance over time. Junior trainees are best suited for this style of training where they stand to make the greatest strides in their development. However, high-quality randomised control trials are needed to establish the clinical benefits of simulation training, sustainability of improvements, transferability of skills and its cost-effectiveness.

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7 Declarations of interest

None

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Figure Legends

Figure 1: PRISMA Flow Diagram - Summary of the study selection process

Table I: Types, advantages, and disadvantages of different technical skill simulators

Table II: Inclusion and exclusion criteria

Table III: Search syntaxes and search strategy

Table IV: The role of endovascular simulation in the acquisition of skill. A summary of the included studies

Table V: Research quality assessment

Appendices

Appendix A: Abstract screening tool

Article title:

1) Is the article an opinion piece, editorial letter, commentary, literature review or systematic review?

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

2) Does the study describe an endovascular technique or procedure not included within the pre-specified list? (Table I)

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

3) Does the study fail to utilise (high-fidelity) simulation as an educational intervention for the endovascular techniques or procedures within the pre-specified list? (Table I)

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

4) Does the study fail to describe outcomes relating to technical or procedural performance through endovascular simulation?

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

5) Does the study fail to describe baseline and end-point measures relating to technical or procedural performance through simulation?

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

6) Does the study fail to include medical students, junior doctors (or equivalent) or consultants (or equivalent)?

   Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

7) Is an English translation of the article not available?

Yes (reject) ☐ No or unknown (proceed to full-text assessment) ☐

Outcome:

Reject ☐ Reason:

Proceed to full-text screening ☐

Appendix B: Full-text assessment tool

Article title:

1) Is the article an opinion piece, editorial letter, commentary, literature review or systematic review?

   Yes (reject) ☐ No (continue to next question) ☐

2) Does the study describe an endovascular technique or procedure included within the pre-specified list? (Table I)

   Yes ☐ No (reject paper) ☐

3) Does the study utilise (high-fidelity) simulation as an educational intervention for the endovascular techniques or procedures within the pre-specified list? (Table I)

   Yes ☐ No (reject paper) ☐

4) Does the study describe outcomes relating to technical or procedural performance through endovascular simulation?

   Yes ☐ No (reject paper) ☐

5) Does the study describe baseline and end-point measures relating to technical or procedural performance through simulation?

   Yes ☐ No (reject paper) ☐

6) Does the study include medical students, junior doctors (or equivalent) or consultants (or equivalent)?

   Yes ☐ No (reject paper) ☐

Outcome:

Reject ☐ Reason:

For inclusion in final review ☐

Appendix C: Quality assessment tool

Article title:

<u>Background and objectives</u>

Has a review of the literature been described? (RMQ)

Yes ☐ No ☐

Is there a clearly-defined and well-described objective to the study? (RMQ)

Yes ☐ No ☐

<u>Research design</u>

Is the design appropriate to answer the research question? (RMQ)

Yes ☐ No ☐

Is the study design explicitly reported? (RQ)

Yes ☐ No ☐

Was a control group used? (RMQ)

Yes ☐ No ☐

Was there any form of randomisation between groups? (RMQ)

Yes ☐ No ☐

Were the learner characteristics reported? (RQ)

Yes ☐ No ☐

<u>Education intervention</u>

Is the educational intervention clearly described? (RQ)

☐ Clear description of the educational intervention that is sufficient to facilitate replication

☐ Some limited description that will not facilitate replication

☐ No

Are the resources utilised clearly described? (RQ)

☐ Clear description of the resources required to deliver the educational intervention that is sufficient to facilitate replication

☐ Some limited description of the resources required that is insufficient to replicate

☐ No

Is there a description of theoretical models or conceptual frameworks that underpin the choice of education intervention? (RQ)

☐ Clear and relevant description

☐ Some limited discussion of underpinning, with minimal interpretation in the context of the education intervention delivered

☐ No

<u>Assessment</u>

Is there a description of the process and outcomes of the assessment? (RQ)

☐ Clear description of the process and outcomes of the assessment

☐ Some limited description that will not facilitate replication

☐ No

Is there a description of theoretical models or conceptual frameworks that underpin the choice of assessment? (RQ)

☐ Clear and relevant description

☐ Some limited discussion of underpinning, with minimal interpretation in the context of the assessment choice

☐ No

Is the educational context of the assessment provided? (RQ)

☐ Clear description of the educational context

☐ Some limited description of the educational context

☐ No

Are there details of psychometrics and how they are applied to the assessment? (RQ)

☐ Clear description of relevant psychometrics and how they are applied to the assessment

☐ Some psychometric information, but not enough to fully inform for dissemination

☐ No

Is there provision of material to allow assessment replication? (RQ)

☐ Clear description of the process and outcomes of the assessment

☐ Some limited description that will not facilitate replication

☐ No

Results and conclusions (RQ)

Do the outcomes match the objectives of the study?

Yes ☐ No ☐

To what extent do the conclusions match the findings of the study? (score 1 – 5) (RQ)

1 – No clear conclusions can be drawn. Not significant
2 – Results ambiguous, but there appears to be a trend.
3 – Conclusions can probably be based on the results.
4 – Results are clear and very likely to be true.
5 – Results are unequivocal.

Are the limitations of the study discussed appropriately? (RQ)

☐ Clear and detailed discussion of the limitations and the implications of these on the results and drawn conclusions

☐ Some discussion of the limitations of the study, but lacking in detail, completeness or linkage to the results and drawn conclusions

☐ No

Are statistical tests used appropriately? (RMQ)

Yes ☐ No ☐

Code the level of impact being studied: (RQ)

☐ Level 1 - Participation

☐ Level 2a - Modification of attitudes/perceptions

☐ Level 2b - Modification of knowledge/skills

☐ Level 3 - Behavioural change

☐ Level 4a - Change in organizational practice

☐ Level 4b - Benefits to patient / clients

Appendix D: Data extraction tool

Demographics and study design

Article title:

Authors:

Year of publication: Country of publication:

Study type:

Participants:

Study aims:

Simulation intervention

Description of the educational intervention (including simulator used):

Specific endovascular procedure:

Assessment tool

Description on performance evaluation

Outcome measures:

Results and conclusions

Main results:

Conclusions:

Table I: Types, advantages, and disadvantages of different technical skill simulators

Simulation Type	Examples	Advantages	Disadvantages
Task Training Simulation	• Cannulation arm • Box trainers • Suture mats • Injection pads	• Relatively cheap. • Easy to implement. • Suitable for low resource settings. • Suitable for early stages in clinical practise. • Allows for a technical skill to be broken down into the essential component steps or simulating an isolated skill in its own right	• Low fidelity • Does not allow for the replication of the full clinical encounter. • Requires additional equipment to create a more realistic experience. • Lack of objective feedback from simulator.
Animal/Cadaveric/Wet-Lab Simulation	• Live or dissected animal tissue material • Human tissue/cadavers	• Provides a high-fidelity experience including anatomical variations. • Allows for simulation of an entire procedure. • Compatible with imaging (ultrasound/fluoroscopy) during the simulation.	• Finite limited resource. • Costly. • Single use. • Require specialist facilities with appropriate licensing and ethical consideration. • Infection risks. • Cannot simulate active bleeding
Virtual and augmented reality	• Computer based simulation models. • Minimally invasive/robotic surgery simulators.	• High fidelity. • Wide range of procedural simulations available. • Detailed objective simulator feedback. • Easily accessible.	• Limited use of adjuvant imaging modalities • Cost associated with setting up and maintenance. • Lack of validated assessment protocols.

		• Limited support faculty required. • Haptic feedback. • Re-usable. • Wide range of simulation options ranging from specific skill through to full procedures • Allows for patient-specific practise by pre-loading with patient's CT/MRI.	
Manikins	• Resuscitation models • Trauma models • Neonatal/paediatric models • Obstetric models • Ultrasound trainers	• Wide range of differing fidelity models available. • Ability to replicate physiological response. • Programmable. • Compatibility with ultrasound imaging. • Can be used as part of a hybrid simulation. • Detailed performance data collected.	• Limited suitability for simulating surgical procedures. • Not suitable for repeated use in invasive procedures without replacing damaged parts. • Cost associated with setting up and maintenance.

Table II: Inclusion and exclusion criteria

Criteria type	Inclusion criteria	Exclusion criteria
Study design	Any study design that describes simulation as an education intervention focused on any of the following endovascular techniques / procedures • EVAR (Endovascular Aneurysm Repair) • TEVAR (Thoracic Endovascular Aortic Repair) • BEVAR (Branched Endovascular Aortic Repair) • FEVAR (Fenestrated Endovascular Aortic Repair) • chEVAR (chimney Endovascular Aortic Repair) • EVAS (Endovascular Aneurysm Sealing) • chEVAS (chimney Endovascular Aneurysm Sealing) • Covered Endovascular Reconstruction of Aortic Bifurcation (CERAB) • Peripheral angioplasty • Carotid artery stenting	Opinion pieces, editorial letters, commentaries, literature review or systematic review which fails to describe simulation as an education intervention focused on any of the techniques / procedures described previously.
Intervention	Any study which utilises high-fidelity (virtual reality) simulation	Any study which fails to use (high-fidelity) simulation as

	as the education intervention for the above techniques / procedures.	the education intervention for the above techniques / procedures.
Outcome	Any study which describes baseline and end-point measures relating to technical or procedural performance through simulation in relation to the above endovascular techniques / procedures. Studies that describe outcomes at all levels of Kirkpatrick's adapted hierarchy are eligible.	Any study which fails to describe outcomes relating to technical or procedural performance through simulation in relation to the above endovascular techniques / procedures.
Participants	Any study which includes medical students, junior doctors (or equivalent) and consultants (or equivalent).	Any study which fails to include medical students, junior doctors (or equivalent) and consultants (or equivalent).
Language	Any country, any language, with translation if needed.	English translation is not available.

Table III: Search syntaxes and search strategy

Stage	Adjoining word	Search term	Field to search
1	AND	*ENDOVASCULAR ANEURYSM REPAIR/ OR *ENDOVASCULAR ANEURYSM SEALING/ OR ((Angioplasty NOT cardiac) OR "aortic aneurysm" OR "aortic dissection" OR BEVAR OR "Branched Endovascular Aortic Repair" OR "Carotid artery stent*" OR chEVAR OR "chimney Endovascular Aortic Repair" OR chEVAS OR "chimney Endovascular Aneurysm Sealing" OR "Covered Endovascular Reconstruction of Aortic Bifurcation" OR endovascular OR EVAR OR "Endovascular Aneurysm Repair" OR EVAS OR "Endovascular Aneurysm Sealing" OR FEVAR OR "Fenestrated Endovascular Aortic Repair" OR "peripheral angioplasty" OR "Peripheral vascular disease" OR PVD OR TEVAR OR "Thoracic Endovascular Aortic Repair" OR "Varicose veins")	Title
		("virtual reality" OR virtual-reality OR VR OR "task trainer*" OR dry-lab OR "dry lab" OR "computer assisted" OR "computer aided" OR simulat*)	Title

Table IV: The role of endovascular simulation in [illegible]

Demographics and study design						Simulation intervention		Assessment tool		Main results summary
Author	**Year**	**Location**	**Study type**	**Participants**	**Study aims**	**Educational intervention**	**Endovascular procedure**	**Performance evaluation**	**Outcome measures**	
Vento et al. [39]	2018	Italy	Case control	n = 10 10 vascular surgery residents	To evaluate the effect of EVAR simulation in boosting the learning curve by quantifying the performance improvement through participation in a series of simulated EVAR procedures.	Participants in the 'training group' received three simulation sessions composed of 6 EVAR cases (over a two-week period). All participants completed 2 EVAR cases (1 simple and 1 complex) at the start and end of the study. The simulator used was the endovascular angio mentor dual slim simulator.	Not specified.	The quantitative evaluation was provided by simulator metrics. The qualitative evaluation was an adapted Likert-scale.	Total procedural time Total fluoroscopy time Time for contralateral gate cannulation Contrast medium volume	Significant improvements in total procedure time, fluoroscopy time and total contrast volume use.
Gosling et al. [35]	2017	USA	Observational	n = 12 4 students 4 junior surgery residents (postgraduate year 1 – 3) 4 senior surgery residents (postgraduate year 4 – 7)	To determine how simulating carotid stenting procedures affects objective performance measures in operators of different experience levels	Over a four-week period, participants completed four simulated carotid artery stenting scenarios. The simulator used was Angio Mentor Dual Sim.	Carotid artery stenosis stenting.	The VR simulator calculated metrics regarding performance at the end of each scenario. Qualitative assessments of operator proficiency were performed with a Likert scale, scored by trained investigators. This allowed for determination of improvement in performance as students progressed through the four scenarios, with the primary outcome measures comparing performance in the first and fourth iteration.	Total procedural time Cumulative fluoroscopy time Contrast agent volume used Likert-scale (subjective performance assessment)	Significant improvements in total procedure time, fluoroscopy time but no significant difference in total contrast volume use.
Kim et al. [45]	2016	USA	Observational	n = 6 3 junior surgery residents (no prior independent endovascular experience) 3 experienced EVAR surgeons	To assess the ability of operators to adopt new skills.	Each participant performed variations of 18 simulations, with each case being classified based on the degree of infrarenal angulation (0 – 20°, 21 – 40° and 41 - 66°). In total, each participant performed 72 simulated EVARs (variations of main body access, type of stent graft system). The simulator used was the Angio Mentor Dual Slim.	Endovascular aneurysm repair (EVAR)	The simulation device provided information on clinical metrics following each clinical case. The actual seal zone coverage by the deployed stent graft was calculated mathematically. Comparison in performance between the first and last 10 cases allowed for determination of procedural improvement	Degree of proximal seal covered by the deployed stent graft Total procedure time Fluoroscopy time Ordinal ranking system used to grade the deployment trials as acceptable or unacceptable based on the distance of the proximal endograft to the lowest renal artery. (1 = optimal, 4 least optimal)	Significant improvements in total procedure time and fluoroscopy time.
Saratzis et al. [5]	2017	UK	Observational	n = 16 16 vascular surgical trainees	To assess the role of SBT using a high-fidelity VR simulator.	Participants performed an EVAR procedure, followed by four supervised SBT sessions (supervisor was a consultant surgeon or radiologist) over a period of three months, followed by performing the same EVAR procedure that was performed at baseline. The simulator used was the Angiomentor VR Simulator.	Non-ruptured infrarenal EVAR	The simulator automatically records a variety of parameters throughout the procedure. Response to training was quantified through comparison of pre-and-post intervention performance. A modified-Likert scale was used to assess trainee performance (by an independent investigator)	Time Amount of contrast medium used Contact of wires(s) and catheter(s) with vessel wall Presence of endoleak Modified Likert scale score	Significant improvements in total procedure time.
Kendrick et al. [46]	2015	USA	Observational	n = 12 4 students 4 junior surgery residents (postgraduate year 1 – 3) 4 senior surgery residents (postgraduate year 4 – 7)	To quantify trainee improvement through participation in a series of TEVAR-specific simulations.	Participants performed a TEVAR simulation case on four separate occasions with a minimum of five days between the sessions. The simulator used was the Angio Mentor Dual Slim.	Thoracic endovascular aortic repair (TEVAR)	The simulation device provided information on clinical metrics following each session. A Likert-scale qualitative analysis was used to evaluate participant proficiency during each simulation, performed by a qualified thoracic vascular surgeon with thoracic aortic experience. Change in performance between the first and last cases were analysed in conjunction with scoring from a Likert-scale qualitative scale, as adapted from Chaer et al.	Total procedural time Total fluoroscopy time Total contrast volume Likert-scale (subjective performance assessment)	Significant improvements in total procedure time, fluoroscopy time but no significant difference in total contrast volume use.

Mattos et al. [42]	2012	USA	Observational	n = 5 4 vascular surgery fellows 1 radiology resident	Describing the experience in venous endovascular simulation training for performance of diagnostic venography and inferior vena cava (IVC) filter placement.	Each participant performed 20 non-selective cavagrams, 20 selective bilateral renal vein venograms and 20 IVC filter placements. The simulator used was the VIST simulator.	Endovascular renal procedures (renal vein venograms, IVC filter placements and cavagrams).	Internal (simulator-based) and external (physician-developed) metrics were measured and obtained. Improvement in performance was determined through comparing metrics between procedure 1 and procedure 20.	Total procedure time Total fluoroscopy time IVC cavagrams Bilateral renal vein venography IVC filter placement Combined errors IVC filter movement Procedural checklist score (max 42) Global rating scale score (max 95)	Significant improvements in total procedure time but no significant difference in fluoroscopy time.
Mazzaccaro et al. [41]	2012	Italy	Observational	n = 100 50 novice vascular surgery and radiology trainees 50 experienced interventional vascular surgeons and interventional radiologists	To define the use of virtual reality for carotid artery stenosis training in type I and type III aortic arches for novice operators.	Each participants trained on a simulator for two hours whilst receiving feedback about errors and technical skill from experienced tutors. The participants performed a procedure in a right bifurcation carotid stenosis in a type I aortic arch and a right internal carotid stenosis in a type III aortic arch, both before-and-after the learning. The simulator used was the Procedicus VIST system.	Carotid artery stenosis.	Data of performance were collected using a report of some simulator-derived metrics. Improvement in performance was obtained through comparison between pre-and-post intervention scores.	17 metrics including total procedural time, contrast amount, time of scope, time to catheterisation, stent placement accuracy, % of residual stenosis after stenting, % of lesion covered with stent, balloon placement accuracy, % of residual stenosis after ballooning, % of lesions covered with balloon, catheter movements against vessel wall, catheter movements without guidewire, catheter movements near lesion, EPD movements during deployment and EDP movements after deployment	Significant improvements in total procedure time and total contrast volume use.
Coates et al. [37]	2010	UK	Observational	n = 14 14 1st year radiology trainees	To evaluate whether training on a simulated device leads to improved performance.	Participants completed three procedures, followed by a two-hour period of structured training on the simulator, followed by 1 hour of operator-led practice on the device. The participants then performed the same three endovascular procedures.	Flush aortography Selective renal angiography Angioplasty on ipsilateral iliac artery stenosis	Simulator-generated data allowed for comparison between pre-and-post intervention performance. Subjective number of errors made and subjective overall performance.	Total procedural time Total fluoroscopy time Total amount of contrast used Mean number of errors made Subjective overall performance	Significant improvements in total procedure time, fluoroscopy time but no significant difference in total contrast volume use.
Lee et al. [43]	2009	USA	Observational	n = 41 23 first year medical students 15 second year medical students 3 'other' students	To assess the ability of a simulation-based curriculum to improve the technical performance of pre-clinical medical students.	Each participant performed a renal stent procedure (pre-test). The 8-week curriculum consisted of didactic teaching, lectures, and a weekly 90-minute mentored simulator session (carotid, renal, iliac and superficial femoral artery interventions). Course concluded with a final renal stent procedure on the simulator (post-test). The simulator used was the Simbionix Angiomentor.	Renal artery stenosis stenting	Objective procedural measures were determined and reported by the simulator, and subjective performance was graded by severe expert observers using a structured global assessment scale. Improvement in technical skill was measured through the comparison of pre-and-post-intervention performance.	Total procedure time Time to the diagnostic angiogram Time to stent deployment Percent residual stenosis Percent of lesion covered by stent Placement accuracy Fluoroscopy time Volume of contrast injected Activated clotting time Eight-question global assessment score (Likert-scale).	Significant improvements in total procedure time, fluoroscopy time but no significant difference in total contrast volume use.
Van Herzeele et al. [40]	2010	UK	Observational	n = 20 10 third year medical students 10 fourth year medical students	To identify if medical students could acquire the appropriate endovascular skills to perform a renal artery angioplasty and stent procedure on a VR simulator.	Participants treated an identical left-sided nonostial renal artery lesion ten times. An experienced interventionalist rated the performance at the initial and final sessions using generic and procedure-specific rating scales. The simulator used was the VIST.	Non-ostial renal artery lesion	The simulator automatically provides a procedure report for each session. Improvement in performance was ascertained through comparing outcomes in the first iteration to outcomes in the tenth iteration. Additionally, an experienced endovascular interventionalist (external assessment) used two rating scales to assess the candidates.	Procedure time Contrast volume Fluoroscopy time Qualitative metrics	Significant improvements in total procedure time, fluoroscopy time, total contrast volume use and observer scores.
Klass et al. [44]	2008	UK	Observational	n = 12 12 radiology registrars	To characterise the progress of trainees using an interventional simulator trainer	Each participant performed five left renal artery angioplasty over the course of six months. The VIST simulator was used.	Left renal artery angioplasty	The simulation device provided information of clinical metrics following each trial. Progression in metrics over the course of the programme was evaluated. Number of mistakes were recorded.	Total procedure time Fluoroscopy times Number of mistakes.	Significant improvements in total procedure time and fluoroscopy time.

Van Herzeele et al. [49]	2008	UK	Observational	n = 11 11 experienced interventionists 4 interventional cardiologists 4 interventional radiologists 2 neuroradiologists 1 vascular surgeon	To objectively assess psychomotor skills acquisition of experienced interventionalists attending a two-day CAS course, using a VR simulator.	Two-day course using didactic sessions, case reviews, supervised VR simulation and live-cases.	Carotid artery stenting	The quantitative evaluation was provided by simulator metrics. Clinical errors were also measured by blinded video assessment.	Procedure time Contrast volume Fluoroscopic time Delivery-deployment time Error scores Carotid artery spasm Placement accuracy Residual stenosis Lesion coverage	Significant improvements in total procedure time, fluoroscopy time, delivery-deployment time, spasm of internal carotid artery and median number of errors.
Dawson et al. [33]	2007	USA	Observational	n = 9 Vascular surgery residents (fellow) in the first year of vascular speciality training.	To evaluate trainees' technical performance before-and-after individualised training with endovascular simulation.	Two-day endovascular skills programme incorporating high-fidelity endovascular procedure simulation, didactic instruction, computer-based training, and tabletop procedure demonstrations. Within the programme, there was eight hours of simulation-based training. The simulator used was SimSuite.	Iliac angioplasty / stenting.	Performance metrics were automatically measured by the simulator. Change in performance on two index cases performed at the beginning and end of the educational intervention allowed for determination of improvement.	Procedure time Fluoroscopy time Contrast used No of balloon catheters used Number of stents implanted Number of wired used	Significant improvements in total procedure time, fluoroscopy time and total contrast volume use.
Neequaye et al. [48]	2007	UK	RCT	n = 20 20 novice surgical trainees 10 randomised to iliac group 10 randomised to renal group	To determine the nature of skills acquisition on the renal and iliac modules of a commercially-available VR simulator.	Participants completed eight sessions on a VR iliac/renal training module and then crossed over to perform two further VR cases of the other procedure.	Iliac stenting / renal stenting	The quantitative evaluation was provided by simulator metrics.	Procedure time Contrast volume Fluoroscopic time Placement accuracy Residual stenosis Lesion coverage Stent:vessel ratio Maximum stent deployment pressure	Significant improvements in total procedure time but no significant difference in fluoroscopy time and total contrast volume use.
Aggarwal et al. [38]	2006	UK	Observational	n = 20 12 experienced in endovascular procedures (performed > 50 procedures) 8 inexperienced in endovascular procedures (performed < 10 procedures)	To assess the role of a virtual reality simulator for interventional vascular procedures.	Over a two-day period, participants completed six repetitions of the same module (non-ostial left renal artery balloon angioplasty and stent procedure). The simulator used was the VIST simulator.	Non-ostial left renal artery angioplasty and stent procedures.	The VR simulator calculated metrics regarding performance at the end of each repetition. This allowed for determination of improvement in performance as students progressed through the six repetitions, with the primary outcome measures comparing performance after the second and sixth iteration.	Total procedural time Total amount of contrast used Fluoroscopy time	Significant improvements in total procedure time and total contrast use but no significant difference in fluoroscopy time.
Patel et al. [47]	2006	USA	Observational	n = 20 20 interventional cardiologists	To demonstrate the utility of the VIST simulator as a measuring tool for improvement in performance and a reduction in procedural errors on repeat testing during simulated carotid angiography.	An instructional course on carotid angiography and then performed five serial simulated carotid angiograms on the VIST simulator.	Carotid angiogram	The quantitative evaluation was provided by simulator metrics.	Procedure time Fluoroscopy time Contrast volume Composite catheter handling errors	Significant improvements in total procedure time and fluoroscopy time but no significant difference in total contrast volume use.
Dayal et al. [36]	2004	USA	Observational	n = 21 16 general surgery residents (performed < 5 percutaneous angiographic procedures) 5 vascular surgeons (> 300 peripheral interventions)	To evaluate the effectiveness of an endovascular simulator for instruction of novice and experienced interventionalists.	Minimum of 2 hours of individualised catheter-based skill training by an expert interventionalist, with the VIST simulator.	Carotid artery stenosis stenting.	Checklist of procedural steps was completed by an experienced interventionalist during the pre-intervention and post-intervention CAS case. Performance metrics were provided by the simulator. Instructor evaluation of participant technical ability in 4 areas.	Procedure time Fluoroscopy time Contrast used Procedural checklist score Subjective technical skills (catheter manipulation, guide wire manipulation, catheter exchange and monorail technique)	Significant improvements in total procedure time, fluoroscopy time, total contrast volume use, procedure score, catheter and guidewire manipulation.

Hsu et al. [34]	2004	USA	Case control	n = 29 16 untrained in endovascular procedures (performed or assisted in < 50 procedures) 13 trained in endovascular procedures (performed or assisted in > 50 procedures)	To investigate the utility and validity of a simulator in assessment and teaching of endovascular skills.	Practice consisted of a 30-minute to 60-minute proctored session, formally repeating the 8 steps within carotid artery stenting or experimenting with the simulator. The simulator used was the VIST simulator.	Carotid artery stenosis stenting.	The simulator generated a report for each session, relating to important clinical metrics. Change in performance was determined through comparing metrics between the pre-test and post-test. Further analysis between the untrained versus advanced group and practice versus no practice group was performed.	Pass (all 8 steps completed within a 60-minute period) or fail Total time Total contrast material used Total fluoroscopy time Number of tools inserted	Significant improvements in total procedure time but no significant difference in fluoroscopy time and total contrast volume use.

Table V: Research quality assessment

Author / Quality	Vento et al. [39]	Gosling et al. [35]	Kim et al. [45]	Saratzis et al. [5]	Kendrick et al. [46]	Mattos et al. [42]	Mazzaccaro et al. [41]	Coates et al. [37]	Lee et al. [43]	Van Herzeele et al. [49]	Klass et al. [44]	Van Herzeele et al. [40]	Dawson et al. [33]	Neequaye et al. [48]	Aggarwal et al. [38]	Patel et al. [47]	Dayal et al. [36]	Hsu et al. [34]
Background and objectives																		
Has a systematic review of the literature been described?	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Is there a clearly-defined and well-described objective to the study?	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Research design																		
Is the study design appropriate to answer the research question?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Is the study design explicitly reported?	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes	No	No	Yes	No	No	No	Yes
Was a control group used?	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Was there any randomisation between groups?	Yes	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes
Were the learner characteristics reported?	Yes	No	No	Yes	No	No	No	No	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Education intervention																		
Is the educational intervention clearly described?	Clear	Clear	Some	Clear	Some	Some	Some	Some	Clear	Clear	Some	Clear	Some	Clear	Some	Clear	Clear	Clear
Are the resources utilised clearly described?	Some	Some	Some	Clear	Some	No	Some	Some	Some	Clear	Some	Some	Some	Clear	No	Clear	Clear	Clear
Is there a description of theoretical models or conceptual frameworks that underpin the choice of education intervention?	No	No	No	Some	No	No	No	No	No	No	No	Some	No	No	No	No	No	No
Assessment																		
Is there a description of the process and outcomes of the assessment?	Clear	Clear	Clear	Clear	Clear	Some	Clear	Clear	Clear	Clear	Some	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Is there a description of theoretical models or conceptual frameworks that underpin the choice of assessment?	Some	Some	No	Some	Some	No	No	No	Clear	Some	No	Clear	No	No	No	No	No	No
Is the educational context of the assessment provided?	No	No	No	No	Clear	No	No	No	Clear	No	Some	No	Some	No	No	No	No	No
Are there details of psychometrics and how they are applied to the assessment?	No	Some	No	Some	Some	No	Some	Some	Clear	Clear	No	Clear	Some	No	Some	Some	No	Clear
Is there provision of materials to allow assessment replication?	Clear	Clear	Some	Clear	Clear	No	Clear	Some	Clear	Clear	Some	Clear	Some	No	Clear	Clear	Some	Clear
Results and conclusions																		
Do the outcomes match the objectives of the study?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
To what extent do the conclusions match the findings of the study?	4	4	4	4	4	3	4	4	5	4	3	4	4	4	4	4	4	3
Are the limitations of the study discussed appropriately	Some	Clear	Some	Some	Clear	No	Some	Clear	Some	Some	Some	Clear	No	Some	Some	Some	Some	No
Are the statistical tests used appropriate?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Impact																		
Level of Kirkpatrick's hierarchy?	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b	2b

Figure 1: PRISMA Flow Diagram - Summary of the study selection process