Thieme

Importance and potential of simulation training in interventional radiology

Bedeutung und Potenzial des Simulationstrainings in der interventionellen Radiologie

Authors

Kornelia Kreiser[1], Nico Sollmann[2], Martin Renz[3]

Affiliations

1 RKU, Department of Neuroradiology, University Hospital Ulm, Germany

2 Department of Diagnostic and Interventional Radiology, University Hospital Ulm, Germany

3 Departement of Diagnostic and Interventional Neuroradiology, Technical University of Munich Hospital Rechts der Isar, Munchen, Germany

Key words

education, treatment planning, patient-specific rehearsal, hightech simulation, 3D prints

received 01.12.2022
accepted 22.03.2023
published online 03.05.2023

Bibliography

Fortschr Röntgenstr 2023; 195: 883–889
DOI 10.1055/a-2066-8009
ISSN 1438-9029

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence

Dr. Kornelia Kreiser
RKU, Department of Neuroradiology, University Hospital Ulm, Oberer Eselsberg 45, 89081 Ulm, Deutschland
Kornelia.Kreiser@rku.de

ABSTRACT

Background Simulation training is a common method in many medical disciplines and is used to teach content knowledge, manual skills, and team skills without potential patient danger.

Methods Simulation models and methods in interventional radiology are explained. Strengths and weaknesses of both simulators for non-vascular and vascular radiological interventions are highlighted and necessary future developments are addressed.

Results Both custom-made and commercially available phantoms are available for non-vascular interventions. Interventions are performed under ultrasound guidance, with computed tomography assistance, or using mixed-reality methods. The wear and tear of physical phantoms can be countered with in-house production of 3D-printed models. Vascular interventions can be trained on silicone models or hightech simulators. Increasingly, patient-specific anatomies are replicated and simulated pre-intervention. The level of evidence of all procedures is low.

Conclusion Numerous simulation methods are available in interventional radiology. Training on silicone models and hightech simulators for vascular interventions has the potential to reduce procedural time. This is associated with reduced radiation dose for both patient and physician, which can also contribute to improved patient outcome, at least in endovascular stroke treatment. Although a higher level of evidence should be achieved, simulation training should already be integrated into the guidelines of the professional societies and accordingly into the curricula of the radiology departments.

Key Points:

- There are numerous simulation methods for nonvascular and vascular radiologic interventions.
- Puncture models can be purchased commercially or made using 3D printing.
- Silicone models and hightech simulators allow patient-specific training.
- Simulation training reduces intervention time, benefiting both the patient and the physician.
- A higher level of evidence is possible via proof of reduced procedural times.

Citation Format

- Kreiser K, Sollmann N, Renz M. Importance and potential of simulation training in interventional radiology. Fortschr Röntgenstr 2023; 195: 883–889

ZUSAMMENFASSUNG

Hintergrund Simulationstraining ist heute in vielen medizinischen Disziplinen verfügbar und dient der Vermittlung von inhaltlichen Kenntnissen, manuellen Fertigkeiten und Teamfähigkeiten ohne potenzielle Patientengefährdung.

Methode Es wird erläutert, welche Simulationsmodelle und -methoden in der interventionellen Radiologie zur Verfügung stehen. Es werden Stärken und Schwächen sowohl von Simulatoren für nichtvaskuläre als auch vaskuläre radiologische interventionen aufgezeigt und auf nötige zukünftige Entwicklungen eingegangen.

Ergebnisse Für nichtvaskuläre Eingriffe stehen sowohl individuell angefertigte als auch kommerziell erhältliche Phantome zur Verfügung. Die Interventionen laufen entweder unter Ultraschallkontrolle, computertomografisch gestützt oder im Rahmen von Mixed-reality-Methoden ab. Dem Verschleiß physischer Phantome kann mit der Eigenproduktion von 3D-gedruckten Modellen begegnet werden. Vaskuläre Interventionen können an Silikonmodellen oder Hightech-Simulatoren trainiert werden. Immer häufiger werden dabei auch reale Patientenfälle nachgebildet und präinterventionell simuliert. Der Evidenzgrad ist allerdings bei allen genannten Methoden niedrig.

Schlussfolgerung In der interventionellen Radiologie stehen zahlreiche Simulationsmethoden zur Verfügung. Training an Silikonmodellen und Hightech-Simulatoren für vaskuläre Interventionen hat das Potenzial, die prozedurale Dauer zu verringern. Dies ist mit einer verringerten Strahlendosis für Arzt und Patient assoziiert und trägt zumindest in der endovaskulären Schlaganfallbehandlung auch zu einem verbesserten Patientenoutcome bei. Auch wenn ein höherer Evidenzgrad erreicht werden muss, sollte Simulationstraining bereits heute in die Leitlinien der Fachgesellschaften und entsprechend in die Curricula der radiologischen Abteilungen integriert werden.

Kernaussagen:
- Es existieren zahlreiche Simulationsmethoden für nichtvaskuläre und vaskuläre radiologische Interventionen.
- Punktionsmodelle können kommerziell erworben oder mittels 3D-Druck angefertigt werden.
- Silikonmodelle und Hightech-Simulatoren erlauben patientenspezifisches Training.
- Simulationstraining senkt die Interventionsdauer, wovon Patient und Arzt profitieren.
- Eine Steigerung der Evidenz ist über den Nachweis reduzierter prozeduraler Zeiten möglich.

1. Introduction

Every patient has the demand to be treated by highly trained physicians. Every medical treatment should be conducted with the highest level of care and expertise and complications should be identified as well as managed. But how do physicians become experts in their field? Which training methods result in such a high level of professionalism?

In most (non-medical) occupations that require training, the theoretical transfer of knowledge is followed by a phase of practical training using training objects and models. Beginners are only allowed to handle real work orders once a certain level of expertise has been reached. Models, simulated patients, and simulators are playing an increasingly important role in the training of medical students. In contrast, models and test objects are often no longer used in resident training between the acquisition of theoretical knowledge and practical application.

The first "simulators" were developed over 2500 years ago [1]. There are numerous, usually anecdotal, reports from the last century about anatomical models made of wax, wood, or glass as well as mechanical, sometimes hydraulic, devices [2]. The benefit of simulation in medical training is generally acknowledged, but acceptance and frequency of use are increasing only slowly. Today, simulation is widely used primarily in anesthesiology. After the introduction of the mannequin "Resusci Anne" in the 1960 s, numerous further developments led to the current standard. Using computer and remote-controlled training scenarios, anesthesiological emergencies can be trained individually or as a team. These scenarios are regularly used in emergency medical services, medical studies, and medical training [3]. Although simulators are also already commercially available for many obstetric, surgical, and other minimally invasive interventions [4–6], their use is only included in individual cases in national training guidelines [7, 8].

However, particularly in advanced training, practice on models can prepare physicians for the first application in patients and can also be a useful tool for the transfer of practical knowledge. Simulation is an excellent training method for teaching skills particularly in radiology since both diagnostic and interventional methods are already image-based. A Delphi panel of Danish radiologists therefore identified topics that are suitable for simulation-based training. 6 of 13 procedures were interventions [9]:
- Ultrasound-guided biopsy and fine-needle aspiration
- Puncture and drainage
- Renal biopsy and nephrostomy
- Fine-needle biopsy and puncture of the breast
- Computed tomography (CT)-guided biopsy or drainage
- Vascular interventions including angiography.

The following provides an overview of the possible uses, weaknesses, and strengths of simulators both for non-vascular radiological interventions and endovascular radiological interventions. ▶ **Table 1** contains relevant aspects regarding application areas, imaging methods, costs, and degree of realism.

2. Simulators

2.1 Use of simulators in non-vascular radiology

2.1.1. Simulation of ultrasound-guided methods

The diagnostic ultrasound examination technique and ultrasound-guided interventions can be practiced on numerous models. For example, homemade gelatin models [10] in which small objects like medicine capsules can be embedded are cost-effective. In contrast, commercial phantoms of various organ systems made of plastic, resin, or silicone can cost thousands of euros (▶ **Fig. 1a**) [11, 12]. A review by Kahr et al. identified 42 studies

▶ **Table 1** Overview of simulators, fields of application, estimated costs, degree of realism, use of X-rays, and the option of patient-specific training. € < 100 Euro, €€ < 10 000 Euro, €€€ < 50 000 Euro, €€€€ > 50 000 Euro; + = very low; ++ = low, +++ = in some aspects realistic, ++++ = in many aspects realistic.

	Field of application	Available simulators	Estimated costs	Degree of realism	Need for X-ray	Option of patient-specific training
Non-vascular interventions	Ultrasound-guided biopsies, punctures and drainages	gelatin, styrofoam	€	+	no	no
		commercial phantoms (resin, plastic, silicone)	€€	++	no	no
		3D-print (resin, plastic, silicone)	€€	++	no	yes
	Computertomography-guided biopsies, punctures and drainages	gelatin, styrofoam	€	+	only with fluoroscopic technique	no
		commercial phantoms (resin, plastic, silicone)	€€	++		no
		3D-print	€€	++		yes
Vascular interventions	Catheter-based angiographies	commercial silicone models	€€€	+++	optional	no
		3D-print silicone models	€€	+++	optional	yes
		hightech-simulators	€€€€	++++	no	yes

on simulation training of ultrasound-guided procedures but found various methodological deficiencies in each one: Missing control groups, lack of randomization, and testing of success using the same model used in training. Two studies were at least able to identify a reduction of complication rates in subsequent clinical application compared to historical control groups [13]. Moreover, none of the mentioned methods is capable of imitating dynamic examination aspects like respiratory movement or intestinal motility.

A more complex training method for all percutaneous punctures is the use of mixed reality methods. A needle is inserted into a synthetic model under ultrasound guidance. In addition to the 2D ultrasound image, the learner additionally sees the needle within a 3D simulation of the anatomy, e. g. the spine, on a second screen or using virtual reality goggles, thereby facilitating interpretation of the ultrasound image [14–16].

2.1.2. Simulation of computed tomography-guided methods

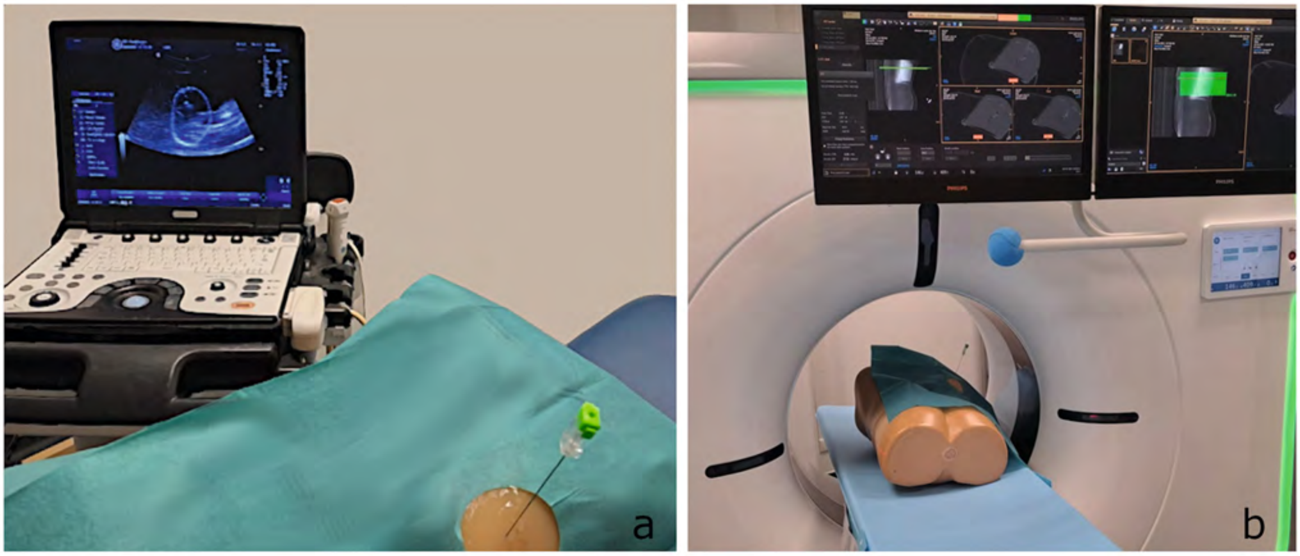
To date, CT-guided interventions have been practiced primarily with phantoms in a real environment, i. e., using radiation [17, 18]. Either homemade or commercially available phantoms are used here (▶ **Fig. 1b**). CT interventions can be performed using sequential cross-sectional images or CT fluoroscopy. In the sequential technique, three slices are usually acquired at a distance of a few millimeters by pressing a pedal or triggering acquisition from the control room in order to check the position of the inserted equipment after each manipulation. The interventionalist can either stay in the room or briefly leave the room. Sequential CT interventions can thus be easily practiced in a real CT environment without the trainee having to be exposed to radiation.

CT fluoroscopy allows image control with greater temporal resolution, which is advantageous e. g. in vertebroplasty. The puncture device is inserted under continuous pulsed radiation and the interventionalist is near the gantry during the entire procedure [19]. Since the radiation dose for patients can even be reduced compared to sequential CT in the case of corresponding expertise with CT fluoroscopy [20], a radiation-free simulator would be useful and desirable particularly here. However, to date, such a simulator has not been mentioned in the literature. In contrast, a puncture technique that is based on primary CT imaging but uses a tracking camera for the insertion of devices was recently described [21]. This method is already used by neurosurgeons and orthopedists in navigation-assisted spinal surgery. It can greatly reduce the use of radiation both in clinical application and in training.

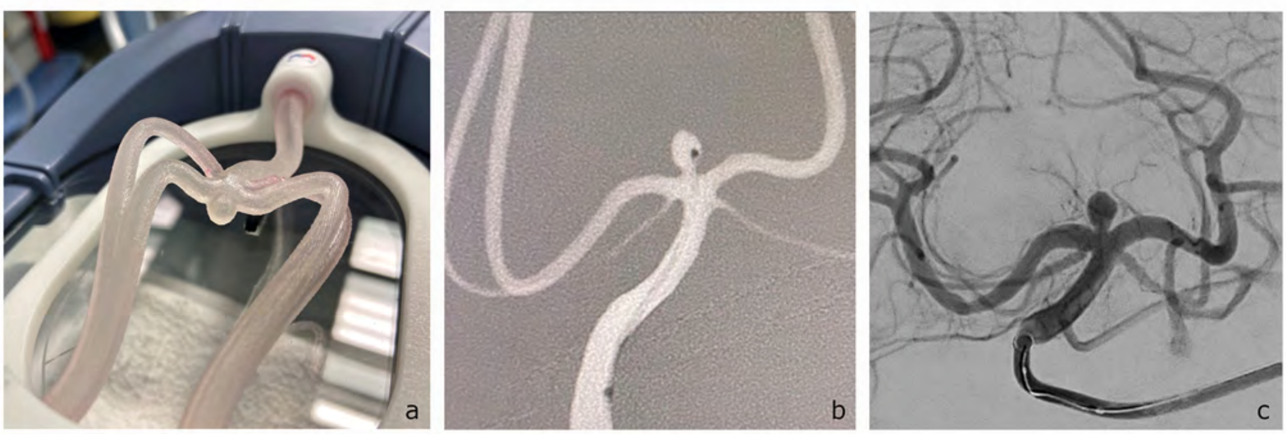
Since all models for CT-guided interventions are similar to those used for ultrasound-guided interventions, respiratory excursion and other organ movements are also not taken into account here.

2.1.3 Use of 3D pressure models

All mentioned methods that require a physical puncture model have one disadvantage in common, namely the phantom wears out and can only be used for a limited number of punctures. The ability to make homemade models made of plastic, resin, or sili-



▶ **Fig. 1** Commercial phantom **a** for ultrasound-guided interventions, **b** for computed tomography-guided interventions.



▶ **Fig. 2** **a** Patient-specific silicone model of basilar tip aneurysm; **b** roadmap technique of silicone model in angiography suite with microcatheter in place; **c** real angiography of patient at the beginning of interventional treatment; courtesy of T. Boeckh-Behrens.

cone with a 3D printer opens up new possibilities not only for the training of physicians but also for the informed consent discussion with patients and preinterventional practice for specific cases. As a result of the reduction in the cost of 3D printers, the repetitive production of models has become increasingly cost-efficient. Tubular vascular models are suitable for practicing the Seldinger technique and probing vessels, while models of individual organs are suitable for practicing biopsies. DICOM (Digital Imaging and Communications in Medicine) datasets of all imaging modalities can be used as a template [22] so that patient-specific interventions can also be practiced.

2.2 Use of simulators in vascular radiology

2.2.1 Silicone models

Transparent silicone models of arteries or veins allow visualization from the outside (▶ **Fig. 2a**). Therefore, the behavior of catheters, stents, and coils as well as the interaction between stent retrievers and (real or synthetic) thrombi can be observed spatially. However, the feel is not comparable with real world conditions because of the significantly higher friction of the materials against the walls of the model. Use of silicone models under fluoroscopy with contrast agent or opaque thrombi is possible but is then of course associated with a certain level of radiation exposure for trainees (and possibly instructors) (▶ **Fig. 2b**). In addition to commercially available models, the use of 3D printers to create models has also been described in the vascular field. Such models for demonstration as well as independent practice are highly valued as teaching materials for medical education [23]. Patient-specific models make it possible to practice an intervention and to test various materials, potentially helping to reduce both the intervention time and the material costs (▶ **Fig. 2c**).

Wu et al. describe the use of such a model of the entire aorta both under fluoroscopy and using an infrared camera. When using an infrared camera, it is not necessary to use an angio suite and lead aprons. The authors also state that the image impression is more realistic than in the case of direct visual or videoscopic viewing of the scene [24].

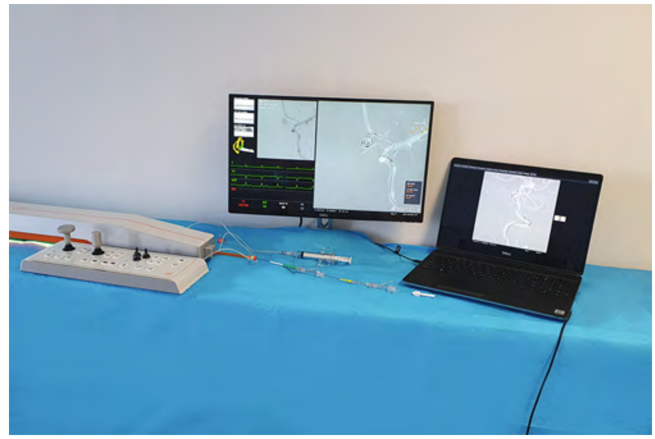
Fluid-filled models can be used to practice the prevention of air embolisms and the correct injection of contrast agents. However it is very difficult to completely remove all air from these systems during preparation. Therefore, this training aspect is usually not included. Some pumps can generate laminar as well as pulsatile flow, but it must be assumed that this has only minimal effect on the behavior of catheters and implants. A greater effect can be expected when using liquid embolic agents or particles. However, in the only available publication on the simulation of chemoembolization of the liver, a laminar flow is used due to technical difficulties [25].

The fact that training with silicone models improves angiographic performance has already been proven for diagnostic neuroangiography [26]. Other authors describe the use of models for case-specific training for arteriovenous renal fistulas [27], splenic artery aneurysms [28], or for the preparation of aortic stent grafts [29]. However, they do not present data regarding the training effects.

2.2.2 Hightech simulators

Hightech simulators have been mostly used in courses in the last two decades but are being increasingly also used for internal training at hospitals (▶ **Fig. 3**). Real catheters whose movement during programmed scenarios can be observed without radiation on monitors are used. The feel of movements (push, pull, and rotation) and resistance, e. g. in very small vessels, is currently relatively realistic. Individual models also use fluids so that users can practice injection rate and the prevention of air bubbles [30]. If the simulator is integrated in an angiography suite, real pedals, monitors, and C-arms can even be used, thus allowing users to practice operating them. This is beneficial particularly when using biplane angiography systems so that residents can concentrate on the individual procedure starting with the first patient [31].

After semiautomatic segmentation of the vessels, patient-specific data can be converted from CT or MR angiography DICOM data into STL files and integrated into the simulator. This does not necessarily require data about the complete anatomy from the puncture site to the target vessel. Missing segments can be supplemented from a selection of templates. Nielsen et al. identified 11 publications on patient-specific simulation training prior to interventions [32]. Five were used to prepare for carotid stenting and six to practice EVAR (endovascular aortic repair) or TEVAR (thoracic endovascular aortic repair) procedures. A decrease in one or more of the following parameters was able to be observed in all studies: Total duration of the procedure, fluoroscopy time, number of series, and contrast agent dose. In addition, the simulation resulted in changes to the planned procedure with respect to access side or size of the implant in some EVAR cases.



▶ **Fig. 3** Hightech simulator showing a coiling procedure of a brain aneurysm.

Not only the patient but also the physician performing the procedure, technicians, and anesthesiologists benefit from a shorter procedure due to the reduced radiation dose. Moreover, a longer intervention time is associated with a higher rate of periprocedural embolisms [33, 34]. Therefore, there are already clear indications that simulation training by physicians benefits patients. However, direct evidence of a reduction of the already relatively low complication rates is significantly more difficult to provide [35].

The simulation of very small or complex anatomical structures, e. g. cerebral aneurysms or arteriovenous malformations, is currently still a clear limitation. This is not yet realistic enough and must be improved significantly in the future. Only then can training benefit beginners as well as experienced radiologists.

3. Summary

There are many indicators that the mentioned simulators can contribute to greater understanding of interventional procedures. The issue with respect to physical phantoms wearing out can be easily resolved today with 3D-printed models. However, there is not yet a solution for the radiation-free training of fluoroscopic CT puncture. There are also no simulators for MRI-guided puncture.

The development of silicone models and hightech simulators for vascular interventions is most developed. In particular, patient-specific training using models of real anatomy prior to interventions seems promising (▶ **Fig. 2**).

4. Outlook

The increasing use of simulation-based training in interventional radiology should result in multicenter efforts to increase the level of evidence of the methods. Particularly since radiation is often used for interventions in radiology, simulation training should be taken advantage of to achieve a measurable reduction of radiation, which has a decisive benefit for both the patient and physician. This is much easier to prove than a decrease in the complication rate, which would require a significant number of patients due to the low rate. In addition, simulation training is highly beneficial for lowering the procedure time particularly in endovascular stroke treatment. The fact that the time factor has a significant effect on patient outcome is being examined for the first time in Norway as part of a national study on the positive effect of simulation training on the national registry data of stroke patients undergoing endovascular treatment [36]. Therefore, in addition to the sporadic application of models and simulators in courses, these methods should also be anchored in structured curricula of radiology departments [31, 37]. The use of simulators as a practice and test modality is already intended in the DeGIR certification curriculum.

Conflict of Interest

K. Kreiser conducts research in areas of interest similar to the business interests of Mentice AB (Gothenburg, Sweden). She gets minor travel compensation, but no personal fees. She consults for Medtronic. The other authors declare that they have no conflict of interest.

References

[1] Badash I, Burtt K, Solorzano CA et al. Innovationen in der Operationssimulation: ein Überblick über vergangene, aktuelle und zukünftige Techniken. Ann Transl Med 2016; 4: 453. doi:10.21037/atm.2016.12.24

[2] Bienstock J, Heuer A. A review on the evolution of simulation-based training to help build a safer future. Medicine 2022; 101: e29503. doi:10.1097/MD.0000000000029503

[3] Rothkrug A, Mahboobi SK. Simulation Training and Skill Assessment in Anesthesiology. 2022 bookchapter in: StatPearls [Internet]. https://www.ncbi.nlm.nih.gov/books/NBK557711/

[4] Satin AJ. Simulation in Obstetrics. Obstet Gynecol 2018; 132 (1): 199–209. doi:10.1097/AOG.0000000000002682

[5] Pietersen PI, Bjerrum F, Tolsgaard MG et al. Standard Setting in Simulation-based Training of Surgical Procedures: A Systematic Review. Ann Surg 2022; 275 (5): 872–882. doi:10.1097/SLA.0000000000005209

[6] Bube SH, Kingo PS, Madsen MG et al. National Implementation of Simulator Training Improves Transurethral Resection of Bladder Tumours in Patients. Eur Urol Open Sci 2022; 39: 29–35. doi:10.1016/j.euros.2022.03.003

[7] https://register.awmf.org/assets/guidelines/015-083l_S3_Vaginale-Geburt-am-Termin_2021-03.pdf abgerufen am 29.11.2022

[8] https://register.awmf.org/de/leitlinien/detail/021-014, abgerufen am 29.11.2022

[9] Nayahangan LJ, Nielsen KR, Albrecht-Beste E et al. Determining procedures for simulation-based training in radiology: a nationwide needs assessment. Eur Radiol 2018; 28 (6): 2319–2327. doi:10.1007/s00330-017-5244-7

[10] https://www.nephro-xperts.de/gelatine-ultraschall-phantome/, abgerufen am 12.11.22

[11] https://medicalskillstrainers.cae.com/ abgerufen am 13.11.22,

[12] https://www.anatomie-modelle.de/Ultraschall-Modelle, abgerufen am 13.11.22

[13] Kahr Rasmussen N, Andersen TT, Carlsen J et al. Simulation-Based Training of Ultrasound-Guided Procedures in Radiology – A Systematic Review. Ultraschall in Med 2019; 40 (5): 584–602. doi:10.1055/a-0896-2714

[14] http://perk.cs.queensu.ca/contents/perktutor abgerufen am 13.11.22;

[15] Freschi C, Parrini S, Dinelli N et al. Hybrid simulation using mixed reality for interventional ultrasound imaging training. Int J CARS 2015; 10: 1109–1115. doi:10.1007/s11548-014-1113-x

[16] Villard PF, Vidal FP, ap Cenydd L et al. Interventional radiology virtual simulator for liver biopsy. Int J Comput Assist Radiol Surg 2014; 9 (2): 255–267. doi:10.1007/s11548-013-0929-0

[17] Picard M, Nelson R, Roebel J et al. Use of Low-Fidelity simulation laboratory training for teaching radiology residents CT-guided procedures. J Am Coll Radiol 2016; 13 (11): 1363–1368. doi:10.1016/j.jacr.2016.05.025

[18] Baadh A, Fadl A, Georgiou N et al. A pilot program for use of a homemade phantom for CT biopsy simulation training. [Abstract No. 376]. J Vasc Interv Radiol 2015; 26 (Suppl. 2): S167

[19] Nakatani M, Kariya S, Ono Y et al. Radiation Exposure and Protection in Computed Tomography Fluoroscopy. Interv Radiol 2022; 7 (2): 49–53. doi:10.22575/interventionalradiology.2022-0010

[20] Cahalane AM, Habibollahi S, Staffa SJ et al. Helical CT versus intermittent CT fluoroscopic guidance for musculoskeletal needle biopsies: impact on radiation exposure, procedure time, diagnostic yield, and adverse events. Skeletal Radiology 2022;. Epub ahead of print. doi:10.1007/s00256-022-04226-y

[21] Van den Bosch V, Salim HS, Chen NZ et al. Augmented Reality-Assisted CT-Guided Puncture: A Phantom Study. Cardiovasc Intervent Radiol 2022; 45 (8): 1173–1177. doi:10.1007/s00270-022-03195-y

[22] Trace AP, Ortiz D, Deal A et al. Radiology's Emerging Role in 3D Printing Applications in Health Care. J Am Coll Radiol 2016; 13: 856–862.e4. doi:10.1016/j.jacr.2016.03.025

[23] Goudie C, Kinnin J, Bartellas M et al. The Use of 3D Printed Vasculature for Simulation-based Medical Education Within Interventional Radiology. Cureus 2019; 11 (4): e4381. doi:10.7759/cureus.4381

[24] Wu TC, Weng JY, Lin CJ et al. Patient-Specific 3D-Print Extracranial Vascular Simulators and Infrared Imaging Platform for Diagnostic Cerebral Angiography Training. Healthcare 2022; 10 (11): 2277. doi:10.3390/healthcare10112277

[25] Aramburu J, Antón R, Fukamizu J et al. In Vitro Model for Simulating Drug Delivery during Balloon-Occluded Transarterial Chemoembolization. Biology 2021; 10 (12): 1341. doi:10.3390/biology10121341

[26] Miranpuri AS, Nickele CM, Akture E et al. Neuroangiography simulation using a silicone model in the angiography suite improves trainee skills. J Neurointerv Surg 2014; 6 (7): 561–564. doi:10.1136/neurintsurg-2013-010826

[27] Morita R, Abo D, Soyama T et al. Usefulness of preoperative simulation with patient-specific hollow vascular models for high-flow renal arteriovenous fistula embolization using a preloading coil-in-plug technique. Radiol Case Rep 2022; 17 (10): 3578–3586. doi:10.1016/j.radcr.2022.07.028

[28] Itagaki MW. Using 3D printed models for planning and guidance during endovascular intervention: a technical advance. Diagn Interv Radiol 2015; 21 (4): 338–341. doi:10.5152/dir.2015.14469

[29] Stana J, Grab M, Kargl R et al. 3D printing in the planning and teaching of endovascular procedures. Radiologie 2022. doi:10.1007/s00117-022-01047-x

[30] https://cathi.de/en/hardware-products#hardware-systems, abgerufen am 30.11.2022

[31] Kreiser K, Gehling K, Zimmer C. Simulation in Angiography – Experiences from 5 Years Teaching, Training, and Research. Fortschr Röntgenstr 2019; 191 (6): 547–552. doi:10.1055/a-0759-2248

[32] Nielsen CA, Lönn L, Konge L et al. Simulation-Based Virtual-Reality Patient-Specific Rehearsal Prior to Endovascular Procedures: A Systematic Review. Diagnostics 2020; 10 (7): 500. doi:10.3390/diagnostics10070500

[33] Chuah KC, Stuckey SL, Berman IG. Silent embolism in diagnostic cerebral angiography: detection with diffusion-weighted imaging. Australas Radiol 2004; 48 (2): 133–138. doi:10.1111/j.1440-1673.2004.01273.x

[34] Bendszus M, Koltzenburg M, Burger R et al. Silent embolism in diagnostic cerebral angiography and neurointerventional procedures: a prospective study. Lancet 1999; 354: 1594–1597. doi:10.1016/S0140-6736(99)07083-X

[35] Kreiser K, Gehling KG, Ströber L et al. Simulation Training in Neuroangiography: Transfer to Reality. Cardiovasc Intervent Radiol 2020; 43 (8): 1184–1191. doi:10.1007/s00270-020-02479-5

[36] Schneider MS, Sandve KO, Kurz KD et al. Metric based virtual simulation training for endovascular thrombectomy improves interventional neuroradiologists' simulator performance. Interventional Neuroradiology 2022. doi:10.1177/15910199221113902

[37] Spiotta AM, Turner RD, Turk AS et al. The case for a milestone-based simulation curriculum in modern neuroendovascular training. J Neurointerv Surg 2016; 8 (4): 429–433. doi:10.1136/neurintsurg-2014-011546