Design and Physical Properties of 3-Dimensional Printed Models Used for Neurointervention: A Systematic Review of the Literature

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BACKGROUND: Three-dimensional (3D) printing has revolutionized training, education, and device testing. Understanding the design and physical properties of 3D-printed models is important.

OBJECTIVE: To systematically review the design, physical properties, accuracy, and experimental outcomes of 3D-printed vascular models used in neurointervention.

METHODS: We conducted a systematic review of the literature between January 1, 2000 and September 30, 2018. Public/Publisher MEDLINE (PubMed), Web of Science, Compendex, Cochrane, and Inspec databases were searched using Medical Subject Heading terms for design and physical attributes of 3D-printed models for neurointervention. Information on design and physical properties like compliance, lubricity, flow system, accuracy, and outcome measures were collected.

RESULTS: A total of 23 articles were included. Nine studies described 3D-printed models for stroke intervention. Tango Plus (Stratasys) was the most common material used to develop these models. Four studies described a population-representative geometry model. All other studies reported patient-specific vascular geometry. Eight studies reported complete reconstruction of the circle of Willis, anterior, and posterior circulation. Four studies reported a model with extracranial vasculature. One prototype study reported compliance and lubricity. Reported circulation systems included manual flushing, programmable pistons, peristaltic, and pulsatile pumps. Outcomes included thrombolysis in cerebral infarction, post-thrombectomy flow restoration, surgical performance, and qualitative feedback.

CONCLUSION: Variations exist in the material, design, and extent of reconstruction of vasculature of 3D-printed models. There is a need for objective characterization of 3D-printed vascular models. We propose the development of population representative 3D-printed models for skill improvement or device testing.

KEY WORDS: Aneurysm, Arteriovenous malformation, Compliance, Lubricity, Neurointervention, Stroke, Three-dimensional (3D) printed model, Tortuosity

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Realistic vascular replicas are important for the evaluation of new devices, training, and education of students, residents and fellows.[1-4] Several different methods of development of 3D vascular replicas have been described. These methods included injection of methyl methacrylate[5-7] into human cadavers to get vascular lumen casts or use of imaging data for rapid prototyping,[8,9] repeated painting,[4,6] dip-spin processing,[10] and a lost wax technique[7] and have been applied to the casts to form vascular replicas with a lumen. These methods

ABBREVIATIONS: ABS, acrylonitrile butadiene styrene; **AVM,** arteriovenous malformation; **COF,** coefficient of friction; **MeSH,** Medical Subject Headings; **MPa,** megapascals; **PRISMA,** Preferred Reporting Items for Systematic Reviews and Meta-Analyses; **3D,** three-dimensional

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were time consuming and resulting models had high surface friction resistance. It was also difficult to achieve precise desired wall thickness.[11]

Alternative options to vascular replicas include cadaveric and animal models.[12,13] They have been used for testing and training for cardiac and other major vessel procedures but using human cadavers to practice intracranial interventions is challenging. Cadaveric vessels shrink and decay, and cadaveric circulation results in edema.[13] To cope with this problem, oily substances have been used as the circulation fluid, which does not mimic blood. Additionally, the evaluation results of a device tested on a cadaver cannot be generalized. Likewise, animal models do not recreate the challenges introduced by diseased vasculature found in humans.

The role of 3-dimensional (3D) printed models (also sometimes referred to as phantoms) in medical training, education, development, and testing of new devices for endovascular and open surgical cerebrovascular diseases is increasing because of the increasing ability to reliably recreate disease states. Several studies have highlighted the utility of 3D printed models for training and education of residents, fellows,[3] and engineers.[1,14,15]

With new model manufacturing techniques, it has become important to look at the physical properties of 3D printed models objectively and to understand the capabilities and limitations of the existing design materials and manufacturing techniques so that expectations and conclusions from their use are framed accordingly. Important physical properties relevant to any vascular 3D printed model include the tortuosity (the geometry), compliance (elastic deformation when a force is applied to the material), and lubricity (capacity for reducing friction). These physical properties can influence performance of catheters and endoluminal devices.[16,17]

In this systematic review of the literature, we evaluated the designs, physical properties, accuracy, and experimental outcomes of 3D printed vascular models developed to provide simulation for neuroendovascular procedures.[3]

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for the reporting this review. The systematic review did not involve human subjects and was exempt from Institutional Review Board approval. We searched Public/Publisher MEDLINE (PubMed), Web of Science, Compendex, Inspec, and Cochrane databases to identify peer reviewed articles describing the use of 3D printed models as prototype and/or for cerebrovascular interventions, training, or education. The literature search was performed by a trained librarian and 2 of the authors. The Medical Subject Headings (MeSH) terms used to perform the literature search are provided in the **Appendix**, **Supplemental Digital Content** (MeSH). We searched the literature published between January 1, 2000 and September 30, 2018. An initial search was performed the first week of September, 2018. A repeat search was performed on the 14th of September, 2018 and again in the first week of October, 2018. Besides online searches of databases, we also searched the bibliographies of all relevant articles. Articles where no English translation was available were excluded. We also excluded articles on 3D printed vascular models aimed for open neurosurgical practice. Articles with no information on the design and properties of 3D printed models were also excluded.

A PRISMA flow diagram was used to demonstrate the number of records at the stages of search and screening. The screening of eligible articles was performed by 2 authors.

Data were extracted by 2 authors after reading the full text articles. Conflicts in data interpretation were resolved with mutual discussion. Information extracted included printer model, material used for printing, patient-specific (based on an individual anatomy) vs population-based (based on anatomy of several individuals) geometry, tortuosity indices, wall compliance, lubrication, and type of fluid and system to control flow rate and pressure. We received no fundig to conduct the systematic review and the protocol for the systematic review was registered online.

RESULTS

A total of 151 records were identified based on the initial search (Figure 1). Twenty-eight articles were identified after removal of duplicates and screening of abstracts. Six articles were excluded after further screening of full texts. A total of 23 articles were thus included in the systematic review.[1,11,15-35] Ten articles described 3D aneurysm models[16,18-21,24-26,33,34] and 2 articles described arteriovenous malformation (AVM) models.[1,15] A total of 9 articles described the use of 3D printed models for stroke intervention[11,17,22,23,29-32,36] and 2 articles described their 3D printed model prototypes.[11,27] Seven articles described 3D printed model prototypes for stroke or aneurysms interventions.[11,18-21,26,27]

Material Used for 3D Printed Models

Twenty three studies specified material used for 3D model preparation (Table 1).[1,11,15-27,29-34,36-39] A total of 5 studies used Tango Plus (elastomer),[17,20,22,23,36] 1 study used stereocol (a photo-polymerized resin), 9 studies used acrylonitrile butadiene styrene (ABS) plastic and silicone, 1 used photosensitive resin, 1 used a polycarbonate-like photoreactive polymer, 1 used polyactic acid and MakerBot Flexible Filament (MakerBot, New York, New York) and another used plaster (zp150 powder and zb6 clear binder). Wetzel et al[27] used a wax model in liquid resin. Sindeev et al[33] used silicone molding around wax. Machi et al[32] used silicone but did not report the technique of 3D printing nor mention the specific 3D printer. Two studies did not specify the material used for 3D printed model in their study (Table 1).

Source Images

A total of 6 studies used computed tomography angiogram as source images for 3D printing,[17,21-23,33,36] 5 studies used magnetic resonance angiograms,[11,15,29-31] 5 used digital subtraction angiograms,[18,19,24,25,34] and 3 used a computed

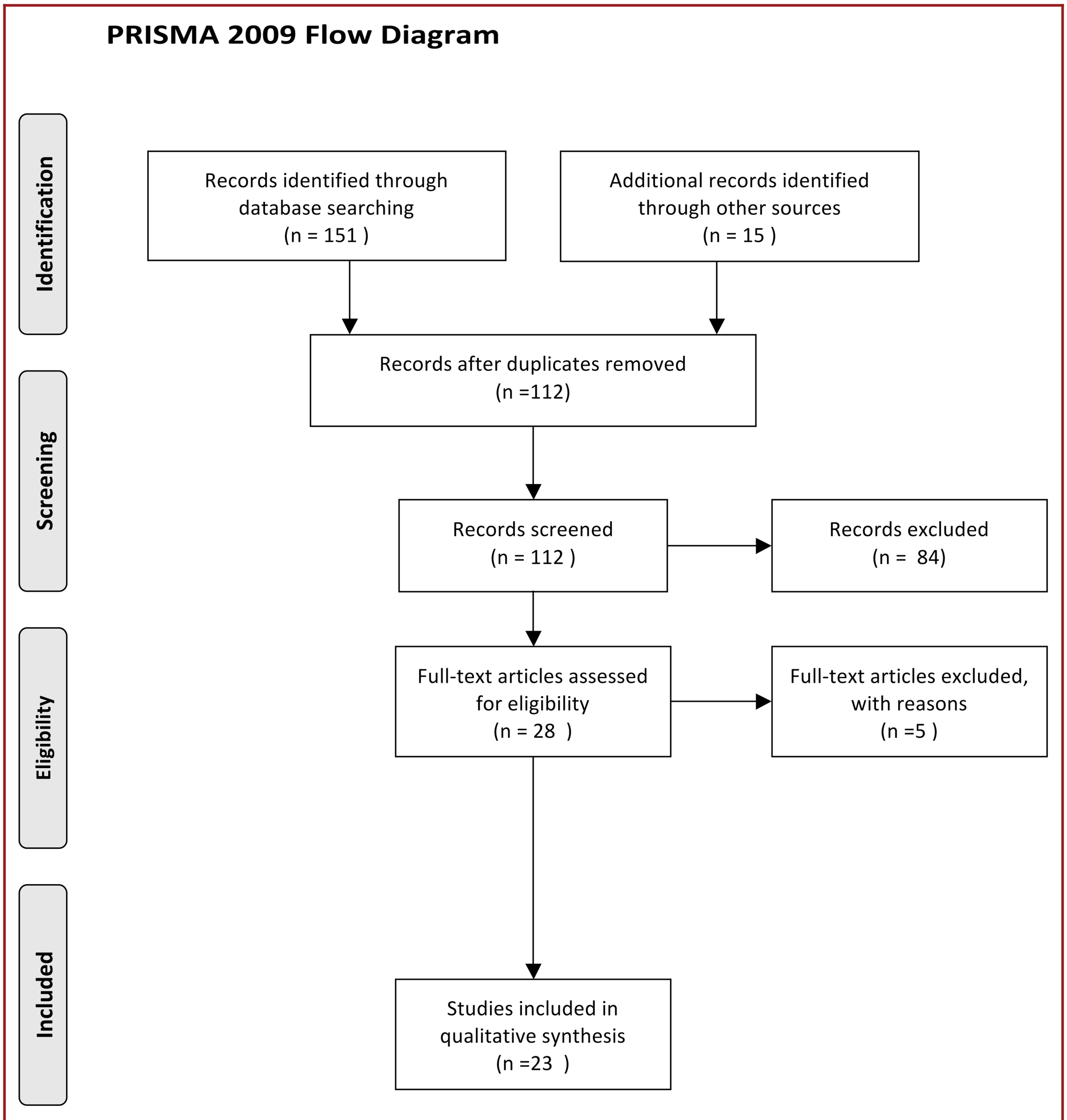

FIGURE 1. *PRISMA flow diagram shows the number of articles searched and excluded at each stage of the literature search after screening titles, abstracts, and full texts.*

tomography angiography, magnetic resonance angiogram, or 3D rotational angiogram.[1,16,26] Dholakia et al[38] did not report the use of any imaging modality. They reported on developing an idealized model.

Geometric Model

All but 4 studies[4,11,29-31] used patient-specific models generated using a 3D angiogram of a specific patient. Chueh et al[11] developed a population-representative vascular model based on the geometric characteristics of 20 patients with normal magnetic resonance angiograms. The model developed was used in subsequent studies by the same group of authors.[29-31]

Extent of 3D Model Vasculature Reconstruction

Eight studies had complete reconstruction of vessels involving extracranial carotids and anterior and posterior circulation with a complete circle of Willis[11,17,22,23,29-31,36] (Table 2). Only 4 studies described the aortic arch as a part of their model.[17,22,23,36] All other studies used a single vessel harboring the pathology, ie, aneurysm or AVM.

TABLE 1. List of Studies Included in the Systematic Review

First authors (year)	Country	Disease of interest	Source data for model geometry patient specific/population representative	Source images	Printer	Material
Sullivan et al 2018[34]	USA	Aneurysm	Patient	DSA	N/A	Silicone
Mokin et al 2018[17]	USA	Stroke	Patient	CTA	Object Model 260 V	TangoPlus
Wang et al 2018[25]	China	Aneurysm	Patient	DSA	Connex Multi-Material	Photosensitive resin
Dong et al 2018[1]	China	AVM	Patient	DSA or CTA	Spectrum Z TM 510	Not reported
Dholakia et al 2018[38]	USA	Aneurysm	Idealized	N/A	Dimension Elite	ABS plastic, molding silicone
Sindeev et al 2018[33]	Germany/ Russia	Aneurysm	Patient	CTA	Acandis (Pforzheim, Germany).	Silicone modled around wax
Kaneko et al 2016[16]	Japan	Aneurysm	Patient	DSA/ CTA/MRA	OPT UP! Plus 2	ABS plastic, molding silicone
Machi et al 2017[32]	France	Stroke	Unclear	Not reported	Not reported	Silicone
Chueh et al 2016[30]	USA	Stroke	Population	MRA	Prodigy Plus	ABS plastic, molding silicone
Frolich et al 2016[19]	Germany	Aneurysm	Patient	DSA	Designjet	ABS
Thawani et al 2016[15]	USA	AVM	Patient	MRA	ProJet 6000	Polycarbonate-like photoreactive polymer
Anderson et al 2016[18]	USA	Aneurysm	Patient	DSA	Replicator 2	Polyactic acid, Makerbot flexible filament
Mokin et al 2016[36]	USA	Stroke	Patient	CTA	Object Model 260 V	TangoPlus
Mokin et al 2015[23]	USA	Stroke	Patient	CTA	Object Model 260 V	TangoPlus
Namba et al 2015[24]	Japan	Aneurysm	Patient	DSA	OPT UP! Plus	ABS plastic, molding silicone
Kondo et al 2015[21]	Japan	Aneurysm (prototype)	Patient	CTA	ZPrinter 450	Plaster (zp150 powder and zb6 clear binder
Mokin et al 2015[22]	USA	Stroke	Patient	CTA	Object Model 260 V,	TangoPlus
Khan et al 2014[20]	USA	Aneurysm	Patient	3D RA	Stratasys Objet 500 Connex	TangoPlus
Chueh et al 2013[31]	USA	Stroke	Population	MRA	Prodigy Plus	ABS plastic, molding silicone
Chueh et al 2012 [29]	USA	Stroke	Population	MRA	Prodigy Plus	ABS plastic, molding silicone
Chueh et al 2009 [11]	USA	Stroke (prototype)	Population	MRA	Prodigy Plus	ABS plastic, molding silicone
Wetzel et al 2005[27]	USA	normal cerebral vasculature/aneurysm	Patient specific	3D RA	ModelMaker II	Wax model in clear liquid resin
Wurm et al 2004[26]	Germany	Aneurysm	Patient specific	3D RA/CTA	SLA 250 and SLA 3500	Stereocol

ABS, acrylonitrile butadiene styrene; AVM, Arteriovenous malformation; DSA, digital subtraction angiography; USA, United States of America; 3D, three-dimensional, 3D RA, 3 dimensional rotational angiography.

Manufacturer list

Connex Multi-Material 3D Printer (MoonRay, Zhejiang, China); Designjet, (Hewlett-Packard Company, Palo Alto, CA); Dimension Elite, Stratasys, Eden Prairie, MN; SLA 250 and SLA 3500, 3500 (3D Systems, Valencia, CA); MakerBot Replicator 2 (MakerBot, New York, New York); ModelMaker II (Solidscape, Merrimack, NH); Objet500 Connex (Stratasys, Eden Prairie, MN); Object Model 260 V (Stratasys, Eden Prairie MN); OPT UP! Plus (OPT, Tokyo Japan); Prodigy Plus (Stratasys, Eden Prairie MN); ProJet 6000 (Z Corp., Rock Hill, SC); Spectrum Z TM 510 (Z Corp., Rock Hill, SC); TangoPlus (Stratasys, Eden Prairie, MN); ZPrinter 450 (Z Corp., Rock Hill, SC).

TABLE 2. Physical Properties of 3D Printed Models Described in Studies in Our Systematic Review

First author (year)	Vascular reconstruction	Arch of aorta	Lubricity	Circulation fluid	Flow system	Outcome measures
Sullivan et al 2018[34]	Parent vessel	No	Not described	Not reported	Not reported	Case rehearsal
Mokin et al 2018[17]	Anterior and posterior circulation	Yes	Not described	60% water, 40% glycerol	Pulsatile Pump	Force required to navigate distal access catheter
Wang et al 2018[25]	Parent vessel	No	Not described	Not reported	Not reported	Qualitative feedback and surveys
Dong et al 2018[1]	Nidus, feeding, and draining vessels.	No	Not described	Not reported	Not reported	Qualitative feedback and surveys
Dholakia et al 2018[38]	Parent vessel	No	Not described	50% water, 50% glycerol	Peristaltic pump	Intra-aneurysmal flow
Sindeev et al 2018[33]	Parent vessel	No	Not described	58% water 42% glycerol	Piston pump	Intra-aneurysmal flow
Kaneko et al 2016[16]	Parent vessel	No	ABS coating	Not reported	Peristaltic Pump	Pre and post coiling aneurysmal flow
Machi et al 2017[32]	ICA, MCA, ACA	No	Not described	Normal saline	Manual flushing	Visual evaluation of clot removal
Chueh et al 2016[30]	Anterior and posterior circulation	No	LSR coating	Saline	Peristaltic pump	Distal embolism
Frolich et al 2016[19]	Parent vessel	No	Not described	Not reported	Not reported	Anatomic precision
Thawani et al 2016[15]	Nidus, feeding, and draining vessels.	No	Not described	Not reported	Not reported	Qualitative feedback and surveys
Anderson et al 2016[18]	Parent vessel	No	Not described	Not reported	Not reported	Feasibility study
Mokin et al 2016[36]	Anterior and posterior circulation	Yes	Not described	60% water, 40% glycerol	Pulsatile Pump	TICI score
Mokin et al 2015[23]	Anterior and posterior circulation	Yes	Not described	60% water, 40% glycerol	Pulsatile Pump	TICI score
Namba et al 2015[24]	Parent vessel	No	Not described	Not reported	Not reported	Catheter shaping
Kondo et al 2015[21]	Parent vessel and skull	No	Not described	Not reported	Not reported	Anatomic Precision
Mokin et al 2015[22]	Anterior and posterior circulation	Yes	Not described	60% water, 40% glycerol	Pulsatile Pump	TICI score
Khan et al 2014[20]	Parent vessel	No	Not described	Not reported	Not reported	Prototyping
Chueh et al 2013[31]	Anterior and posterior circulation	No	LSR coating	Saline	Peristaltic pump	Distal embolism
Chueh et al 2012[29]	Anterior and posterior circulation	No	LSR coating	60% water, 40% glycerol	Programmable piston	Measurement of flow after thrombectomy
Chueh et al 2009[11]	Anterior and posterior circulation	No	LSR coating	60% water, 40% glycerol	Programmable piston pump	Prototyping
Wetzel et al 2005[27]	Parent vessel	No	Not described	Not reported	Not reported	Feasibility study
Wurm et al 2004[26]	Parent vessel	No	Not described	Not reported	Not reported	Prototyping

ABS, acrylonitrile butadiene styrene; ACA, anterior cerebral artery; ICA, internal carotid artery; LSR, liquid silicone rubber; MCA, middle cerebral artery; TICI score, Thrombolysis in cerebral infarction score.
Pulsatile pump manufactured by Masterflex, Cole-Parmer, Vernon Hills, Illinois Programmable piston pump manufactured by Shelley Medical Imaging Technologies, Toronto, Canada.

Compliance and Flow Characteristics of 3D Printed Models

Chueh et al[11] described a tensile test of their silicone strips and compared it to postmortem human middle cerebral artery values. They reported a modulus of 0.67 to 1.15 megapascals (MPa).[11] The value was higher than the 0.42 MPa reported in other postmortem studies.[40] Other studies have not described compliance of 3D printed models. Eleven studies described flow characteristics (Table 2).[11,17,18,22,23,29-33,38] Studies by Mokin et al[17,22,23] described circulation of fluid through the model maintained by a pulsatile pump (Masterflex, Cole-Parmer, Vernon Hills, Illinois) to adjust the flow rate. Studies by Chueh et al[11,29-31] described a flow model where the vascular channels were attached to a programmable piston (Shelley Medical Imaging Technologies, Toronto, Canada), a custom-built starling-resistant chamber, and a data acquisition system. Two Chueh et al[11,29] studies used a mixture of glycerol and water in a 40:60 ratio while saline was used in the latter 2 studies by the same group.[30,31] Mokin et al[17,22,23] used a mixture of glycerol and water in a 40:60 ratio. Although Mokin et al[17,36] do not provide a detailed description of type of fluid in every study, the authors have referred to previous studies where they utilized glycerol and water. Dholakia et al[38] and Sindeev et al[33] also utilized glycerol and water in ratios of 50:50 and 42:58, respectively. Machi et al[32] used manual flushing with normal saline. Kaneko et al[16] used a peristaltic pump (WPX1, Welco, Tokyo, Japan); the nature of the fluid used in their experiment was not reported. Other studies did not describe any flow system.

Lubricity of Vascular Models

The prototype stroke model described by Chueh et al[11] reported coefficient of friction (COF) as a measure of lubricity. The prototype was used in follow-up studies.[11,29-31] A liquid silicone rubber coating was applied to the luminal surface to achieve a COF comparable to the COF observed in cadaveric blood vessels. Kaneko et al[16] applied ABS solvent to smooth the surface of the model and showed a reduction in the force required to navigate a microwire through the vessel.

Experimental Outcome Measures

Different assessment methods were used to determine the outcomes of experiments involving 3D printed models. Three studies used the thrombolysis in cerebral infarction score to assess revascularization after performing a stroke intervention and 2 studies assessed distal embolization after a mechanical thrombectomy.[22,23,30,31,36] In 1 of their studies, Chueh et al[29] measured restoration of flow after thrombectomy to assess revascularization. In a study conducted by Mokin et al,[17] 3D printed models were used to determine and compare forces applied to distal access catheters while navigating through the carotid siphon to the proximal middle cerebral artery. Kaneko et al[16] used pre and post coiling aneurysmal flow to assess the degree of aneurysm occlusion. Dholakia et al and Sindeev et al assessed intra-aneurysmal flow after the deployment of flow diverters.[33,38] Other studies used qualitative feedback and surveys from trainees.[1,15,25] Weinstock et al[41] observed the effect of practice on 3D printed models on the operative times of actual procedure in comparison with matched cases who underwent the procedures without practice on 3D printed models.[41]

Accuracy of 3D Models

Four studies included statistical data regarding the accuracy of their 3D models in comparison to the source imaging.[1,15,21,41] The models used by Dong et al[1] and Thawani et al[15] represented vessel diameters <2 mm and lengths <1 mm. Weinstock et al[41] described 98% accuracy of their model to AVM imaging based on distance from AVM to the ventricle and distance from the nidus to the feeding artery. Kondo et al[21] created and described 3D models of the head with unruptured aneurysms using rapid prototyping recreating a skull with vessel structures. Although bony structures were recreated with significant accuracy ($P < .001$), vessel thicknesses and lengths were significantly different than those measured on the source imaging. To note, all 4 studies utilized different 3D printers and materials for model construction (Table 1).

Limitations of 3D Models

All included articles highlighted positive attributes provided by 3D printed models with respect to increasing awareness of the anatomic complexity of aneurysms and AVMs, aiding in operative planning, and neurosurgical education. Several articles highlighted key disadvantages to applications eg, due to the rigid properties of the stereocol used by Wurm et al[26] in their 3D aneurysm models, in-depth evaluation and simulation of aneurysm neck clipping was not possible. Those investigators noted that vessels <0.4 mm were unable to be recreated in 3D due to failure of source imaging to capture the complete vessel.[26]

DISCUSSION

The design and material characteristics of 3D model printing are especially important for endovascular surgery simulation where interactions between endoluminal devices and vessel walls affect the ease and feasibility of the use of the model. Three-dimensional printed models can only be used for education, training, and testing of devices for clinical application if they are adequately standardized in terms of aforementioned properties. To our knowledge, this is the first systematic review of the structure and physical properties of 3D printed models described in neurointervention studies.

Seven different materials were used to develop 3D printed cerebrovascular models. The variation of materials highlights the heterogeneous nature of models. One study described the compliance.[11] The study by Kaneko et al[16] described the use of ABS solvent to reduce friction by measuring the forces required to navigate before and after applying ABS to the model surface.

Chueh et al[11] used liquid silicone rubber to lubricate the surface and obtain a COF comparable to the properties of a postmortem vessel wall. Other studies have not reported a lubricity or COF.

Three-dimensional model reconstruction was limited to the area of pathology (14 studies) and surrounding vasculature.[1,15,16,18-21,24-27,33,34,38] Such reconstructions may be useful in understanding the spatial relationships of an aneurysm or AVM; however, they are not appropriate for endovascular training or device testing. In endovascular procedures, access to the lesion is as important as the anatomy of the lesion. Therefore, the vascular anatomy should be replicated from femoral access to the lesion, including the aortic arch and extracranial vertebral arteries (for posterior circulation studies) and carotid arteries (for anterior circulation studies). Four studies described a model where an aortic arch and extracranial carotid were part of the 3D model and were used to perform mechanical thrombectomy.[17,22,23,36]

A variety of flow systems were reported. Chueh et al[11,29-31] reported a model that had a chamber to simulate starling forces of peripheral resistance. The studies by Mokin et al[17,22,23,36] and Kaneko et al[16] used a programmable peristaltic pump to generate pulsatile flow to mimic cardiac output. A 60:40 water to glycerol ratio was used by Mokin et al[17,22,23,36] and Chueh et al[11,29-31] and was thought to mimic physiologic properties of blood (Table 2).

Some studies highlight the difficulties in using models for technical practice due to the brittle or rigid nature of material[26] or a lack of ability to simulate real-life behavior, yet there is a need for training on 3D printed models due to the increasing scrutiny of "on-the-job" training during actual patient surgery or treatments.[37] With standardization of physical properties and materials, 3D printed models have tremendous potential to aid in the training of future neurosurgeons. There is also a disagreement on the outcome measures used for experiments using 3D printed models especially for stroke. Some studies used a TICI score to assess the success of reperfusion techniques while others have tried to quantify the flow restoration or distal embolism. It may be prudent to assess all these measures as they have been part of clinical investigations on stroke intervention.

Limitations

There are certain limitations to our systematic review. The protocol was not registered online. We did not include non-indexed or non-peer reviewed articles; however, in addition to biomedical databases we also searched Compendex and the Inspec databases, which index scholarly articles on physics, technology, and engineering. We also did not include articles on 3D printed vascular models not intended for endovascular interventions. Due the heterogeneity and qualitative nature of data, a meta-analysis could not be performed. Our review does not compare 3D printing with methods of developing models and simulation with virtual reality.

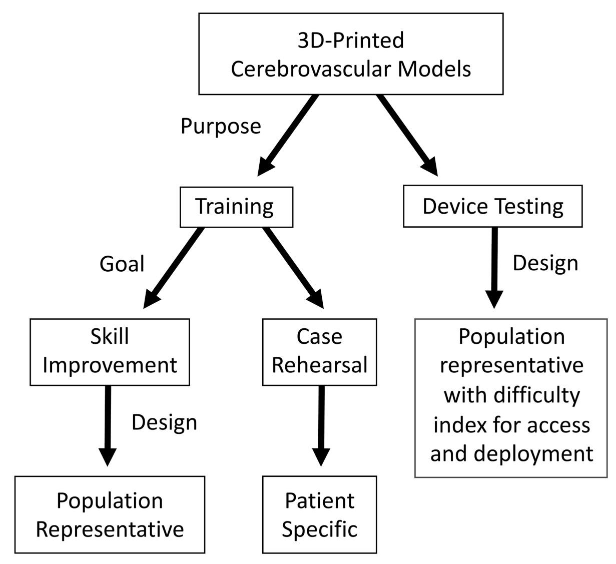

FIGURE 2. *Shows an algorithm selection of an appropriate design of 3D printed models.*

Future of 3D Printed Models for Endovascular Neurosurgery

Future studies should describe the structure and physical characteristics of 3D printed models. Compliance, lubricity, and longevity of the material are important considerations in developing 3D models for neurointervention. The geometry of a 3D printed model can be based on the characteristics of a single patient, ie, patient specific or represent the anatomy of a group of patients, ie, population representative. Though patient-specific 3D models are useful for rehearsing a case, it is imperative that 3D models used for device testing accurately represent a sample population. The geometry of 3D models should represent characteristics of a population with a specific disease. We propose an algorithm to guide the development of 3D printed models for various goals (Figure 2) and 3D printed models that represent the anatomical variations seen in the population of those with a specific disease of interest.

Device testing is an emerging application of 3D printed models. It will be necessary to standardize 3D printed models, in terms of their anatomy and physiology of flow, fluid pressure, and temperature. Recently, the Radiological Society of North America 3D printing Special Interest Group published guidelines for 3D printing appropriateness for clinical scenarios.[42] The group provided recommendations to standardize the process of 3D printing. However, recommendations for 3D printed models specifically outlined for neurointervention are necessary. Appropriate manufacturing controls should also be in place to ensure that designs are repeatedly delivered especially because significant postprocessing after the 3D printing is needed. Recent studies are now exploring the use of 3D printed models to replicate vessel wall pathologies such as stenosis and atherosclerotic plaques.[43] Similarly, attempts have been made to grow endothelial cells on the luminal surface by coating the surface with fibronectin.[39] Future 3D printed vascular models may have an additional endothelial lining that could help our understanding of the impact of hemodynamics on the lining of vessel wall.[39,44]

CONCLUSION

Our review found a large variation in the design, material, extent of reconstruction of cranial and extracranial vasculature, and outcomes of simulation procedures. Most studies have not focused on the physical properties of 3D printed models such as compliance and lubricity of vessel walls. We propose the development of population representative 3D printed models intended for skill improvement and device testing.

Disclosures

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