Int J Clin Exp Med 2020;13(8):5763-5771
www.ijcem.com /ISSN:1940-5901/IJCEM0102437

*Original Article*

# The preliminary application of a 3D printed vascular simulation system in neural intervention training

Junshuan Cui, Jian Liu, Hua Yang, Han Peng, Xu Xu, Jian Yan, Xin Xiang

*Department of Neurosurgery, Affiliated Hospital of Guizhou Medical University, Guiyang, Guizhou, China*

Received September 17, 2019; Accepted December 1, 2019; Epub August 15, 2020; Published August 30, 2020

**Abstract:** Objective: This study aimed to discuss the value of a 3D Printed Vascular Simulation System (3D Simulation System) in neural intervention training. Methods: A total of 12 trainees of neural intervention were randomized into two groups for 3D simulation system training and traditional training to evaluate the advantages and disadvantages of both training methods. The trainees were separated into two groups, the control groups and the simulation group. Trainees in the control group received traditional training, and trainees in the simulation group received a 14-day intensive training during an operation observation period. Results: statistical differences were found in the identification of intervention materials, images and pictures ($P < 0.05$) after the observation period, incidences of complications ($P < 0.01$) in the two groups, operation time of different groups, different arch types and different time segments ($P < 0.01$). Compared with other two arch types, steps for type III/horn aortic arch operations were better mastered; there was a statistical difference between the simulation group and the control group in the inflection point ($P < 0.05$); the learning curve for operations with 3D simulation system enters a steady phase after training with 30 cases, and for traditional training mode, around 40 cases were required to achieve the same effects. Conclusion: trainees who received 3D simulation system training obtained better knowledge about neurovascular anatomy and related interventions faster, and were able to perform angiography earlier, more independently and skillfully. While shortening the time to study preliminary operations and complications related to intervention during training, 3D simulation system training also significantly improved the learning effect of type III and horn aortic arches.

**Keywords:** 3D printed vascular simulation system, neural intervention, simulation training, operation training, learning curve

## Introduction

Neural intervention operation is one of the most powerful means to treat cerebrovascular disease [1]. However, at the present stage, talent in neural interventions are limited, a major factor impeding the dissemination and popularization of neural intervention [2]. Therefore, development of a regulated training for related talents is an important condition for the popularization of this technology. Nowadays, most intervention trainings are carried out under the traditional "apprenticeship" model, which may have problems such as potential medical risks, extended exposure to X-ray, and legal and ethnic concerns [3, 4]. To this end, scholars have proposed a number of trainings schemes [5] based on medical simulation training systems which immensely shorten the training cycle and learning curve [6], remarkably improves catheter technologies mastered by intervention trainees at various stages [5], and facilitates the transfer of the technology to intervention operations in real life [7]. Diversified simulation training systems are available, including VR training systems [3, 7, 8], *in vitro* vascular models [3, 5], cadaver and animal models, which, however, are restricted in precision, mass production or large-scale popularization and application due to their complicated modeling, high cost, and limited biofidelity. Therefore, in this study, 3D printing technology was applied to mold and produce an integrated vascular simulation system characterized by high biofidelity and low cost for explorative application in neural intervention training.

This study combined the learning curves of 12 trainees of neurosurgery, who participated in the traditional training and 3D simulation sys-

**Figure 1.** 3D printing vascular simulation system.

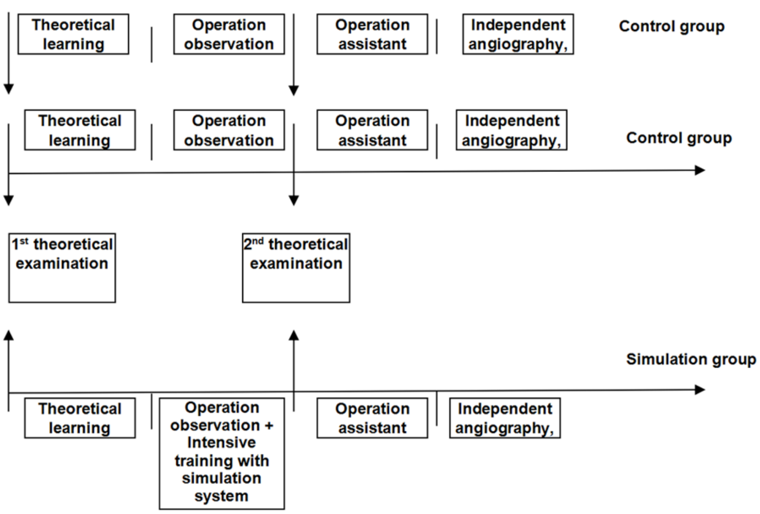


**Figure 2.** Timeline for training processes of neural intervention.

tem training for neural intervention from March 2014 to January 2016, in order to evaluate the feasibility, effectiveness and practicability of the simulation system in intravascular intervention, to compare the advantages and disadvantages of both training methods, and to preliminarily discuss measures to improve the stages of learning curves successfully, effectively and rapidly.

## Materials and method

*Subjects of study*

The subjects of study included Master Degree candidates and doctors engaged in advanced studies, who received training of neurovascular interventions in the Neurosurgery Department of the Affiliated Hospital of Guizhou Medical University from March 2014 to January 2016. Twelve trainees (Tr) were randomly selected and 720 patients (384 males and 333 females) were included according to the criterion that they had received aortocranial angiography by trainees in the study independently.

*Materials*

Materials for simulation system: 3D Printed Vascular Simulation System (**Figure 1**), simulated digital angiography machine and simulated operation table, Ipad 3, wireless camera, etc.; ordinary materials for neural intervention as operating materials.

*Methods*

Assessment of theoretical knowledge (10-point system): 1. Identification rate of nouns used in anatomy (on 3D simulation system). 2. Identification rate of intervention materials. 3. Identification rate of images and pictures (including various distinctive images and pictures). 4. Identification rate of nouns used in intervention technology.

Shown in **Figure 2**, all trainees were assessed for theoretical knowledge before theoretical learning to understand how much knowledge they have mastered in relevant fields before training. Subsequently, they were trained under different models: 1) Trainees of control group received traditional training, in which, they observed at least 20 intervention operations after theoretical learning, and were familiarized with structure, direction and shape of blood vessels, anatomical levels, anatomic landmarks for adjacent structures, and special advancing rules of guide wires and catheters [8] from the 2D perspective under X-ray; with more understanding on operation process of intervention, trainees established perceptual knowledge on neural intervention operations [5]. Following this stage was the second theoretical assessment, and trainees participated in 30 angiographies as the chief assistant; after satisfying all training requirements listed above, they were prepared for angiography, including at least 60 aortocranial angiographies, in an independent and continuous manner. 2) Trainees from the simulation group received a 14-day intensive training during operation observation period, and simulation training for different arch types alternatively until at least 60 cases were done and stability in operation of simulator was achieved. Other training processes remained the same as that of the control group, and followed the sequence of simulation before practicing on patients.

Arch type: classical types of Myla S [9] developed in 2000 were used to group arches into Types I, II and III. Given the high difficulty to be crossed in the intervention, horn aortic arch was listed out separately and designated as Type IV therein.

Recording of operation time: since a significant number of data for effective time of angiography on the right vertebral artery were missing, the angiography time of the right vertebral artery was removed to guarantee data consistency and accuracy. The time for intervention operation herein was the sum of time for angiography of internal carotid arteries on both sides and the left vertebral artery, and the time for operating simulator included time for angiography of internal carotid arteries and vertebral arteries on both sides.

Partial indexes were divided into 5 groups equally according to the sequence of intervention operations, and the remaining ones were included in Group 5. The 5 groups were named as Time Segments 1, 2, 3, 4 and 5 respectively.

The inclusion criteria for the patients included the following: 1) patients included Master Degree candidates and doctors but without relevant complications; 2) patients diagnosed for the first time; 3) patients who received training of neurovascular intervention. The exclusion criteria for the patients were as follows: 1) patients who had received aortocranial angiography and other diseases; 2) patients who had undergone treatment before admission; 3) patients who died during the follow-up.

### *Statistical analysis*

SPSS 23.0 was employed for statistical processing, and measurement data were compared between the two groups by *t* test if normality and homoscedasticity were satisfied, or by rank-sum test in other cases. Nominal data were statistically described with relative numbers, and statistically analyzed by chi-square test; where conditions for chi-square test were not satisfied, Fisher exact probability method was applied. To compare the operation time of the two groups, ANOVA of factorial design was adopted, and the calculations of inflection points on learning curves were statistically analyzed by curve fitting + secondary derivation, with test level $\alpha=0.05$.

## Results

### *Comparison of basic conditions for different arch types and different groups*

I. Information of trainees: the two groups were basically similar in distribution of gender, number, corrected visual acuity and title, and had no statistical differences in age, height and period of involvement in operations ($P > 0.05$).

II. Theoretical assessment score: there was statistical difference between the simulation group and the control group in the time points of identifying intervention materials, images and pictures after operation observation period ($P < 0.05$), and differences in other items and time points were not statistically significant.

III. Background data of patients (**Table 1**): compared as a whole, there was no statistical difference between the two groups in gender, age and BMI ($P > 0.05$). Data were distributed according to arch types for comparison. Patients of arch type I were relatively young, while patients in other arch types and different groups of different arch types had no statistical differences in gender, age and BMI. There was no statistical difference between the two groups in distribution of arch types (**Table 2**) ($P > 0.05$).

### *Comparison of operation time (minutes) for different arch types and different group types in different time segments*

IV. Complications: after operation, blood effused from the point of puncture due to improper

**Table 1.** Comparison of basic conditions for different arch types and different groups ($\overline{X}$±S)

| Arch type | Group | Gender [n/N (%)] Male | Age (Year) | BMI |
|---|---|---|---|---|
| I | Simulation group | 62/129 (53.45) | 50.17 ± 17.19 | 23.40 ± 3.65 |
| | Control group | 67/129 (53.17) | 47.02 ± 17.58 | 22.86 ± 3.07 |
| II | Simulation group | 99/192 (55.93) | 50.92 ± 15.14 | 23.04 ± 3.17 |
| | Control group | 93/192 (54.07) | 52.24 ± 15.37 | 23.13 ± 3.26 |
| III/IV | Simulation group | 38/65 (57.58) | 53.30 ± 14.83 | 22.73 ± 4.66 |
| | Control group | 27/65 (43.55) | 54.79 ± 17.23 | 23.47 ± 3.12 |

**Table 2.** Comparison of different groups of aortic arch type distribution [n/N (%)]

| Group Type | Arch type | | | |
|---|---|---|---|---|
| | I | II | III | IV |
| Simulation group | 116/360 (32.22) | 178/360 (49.44) | 50/360 (13.89) | 16/360 (4.44) |
| Control group | 126/360 (35.00) | 172/360 (47.78) | 42/360 (11.67) | 20/360 (5.56) |

**Table 3.** Comparison of Operation Time (Minutes) for Different Arch Types and Different Group Types in Different Time Segments ($\overline{X}$±S)

| Arch Type | Group Type | Time Segment 1 | Time Segment 2 | Time Segment 3 | Time Segment 4 | Time Segment 5 |
|---|---|---|---|---|---|---|
| I | Simulation group | 23.29 ± 6.98 | 19.00 ± 5.18 | 15.96 ± 2.48 | 14.13 ± 1.87 | 13.45 ± 1.36 |
| | Control group | 31.50 ± 9.11 | 21.63 ± 5.91 | 19.29 ± 4.29 | 15.13 ± 1.60 | 14.40 ± 1.48 |
| II | Simulation group | 26.31 ± 6.52 | 19.53 ± 3.20 | 17.36 ± 2.29 | 16.25 ± 2.16 | 15.48 ± 1.94 |
| | Control group | 36.86 ± 6.85 | 24.61 ± 5.00 | 21.14 ± 4.45 | 16.97 ± 3.52 | 15.18 ± 2.39 |
| III/IV | Simulation group | 29.83 ± 6.07 | 23.25 ± 5.01 | 19.42 ± 2.71 | 18.17 ± 1.90 | 16.00 ± 2.22 |
| | Control group | 41.67 ± 7.62 | 33.83 ± 11.47 | 26.58 ± 7.50 | 20.50 ± 4.30 | 16.79 ± 1.89 |

bandaging or patients' failure to comply with the doctor's suggestions for immobilization, according to clinical observation. Therefore, with such patients removed, the total cases of complications were 22 in the control group and 8 in the simulation group, which had statistical difference after chi-square test ($P < 0.05$).

V. Operation time: operation time for different arch types had significant statistical differences ($P < 0.01$), indicating the greatest influence of arch types on it. Therefore, arch types were compared hierarchically, and data were divided into 5 segments according to sequence of operation time for comparison. The total time taken by different groups had significant statistical differences ($P < 0.01$), namely, compared with the control group, simulation group spent less time in total, and mastered the operation steps faster. The total time taken in different time segments had significant statistical differences ($P < 0.01$), and further pairwise comparison revealed the statistical significance of the differences in each time segment, namely, as time went by (number of operations increased), total time reduced gradually. There was a statistical difference ($P < 0.05$) between different group types in segments 1-4, and the two groups had no statistical difference in time segment 5 ($P > 0.05$), indicating that the operation time at later period tended to be consistent; however, for simulation a group statistical difference was observed in pairwise comparison in time segments 1-4 ($P < 0.05$), but there was no statistical difference in time periods 4 and 5 ($P > 0.05$), revealing that the simulation group entered into the steady phase ahead of the control group (**Tables 3** and **4**).

*Variance in the operation time of simulation group and control group for different arch type*

As shown in **Figure 3**, total time varies significantly with group types and arch types. Arch types I and II are closer in total time, while the difference of arch types III/IV is more significant in the control group, indicating the possible role of exercise with simulation in improving

**Table 4.** Results of ANOVA of factorial design

| Factor | *SS* | DF | *MS* | *F* | *P* |
|---|---|---|---|---|---|
| Group | 3280.17 | 1 | 3280.17 | 143.81 | < 0.001 |
| Arch type | 2758.60 | 2 | 1379.30 | 60.47 | < 0.001 |
| Time segment | 19427.87 | 4 | 4856.97 | 212.94 | < 0.001 |
| Group * Arch type | 256.55 | 2 | 128.28 | 5.62 | 0.004 |
| Group * Time segment | 1789.07 | 4 | 447.27 | 19.61 | < 0.001 |
| Arch type * Time segment | 600.47 | 8 | 75.06 | 3.29 | 0.001 |

Comparison of number of failures: no statistical difference between the two groups (*P* > 0.05).

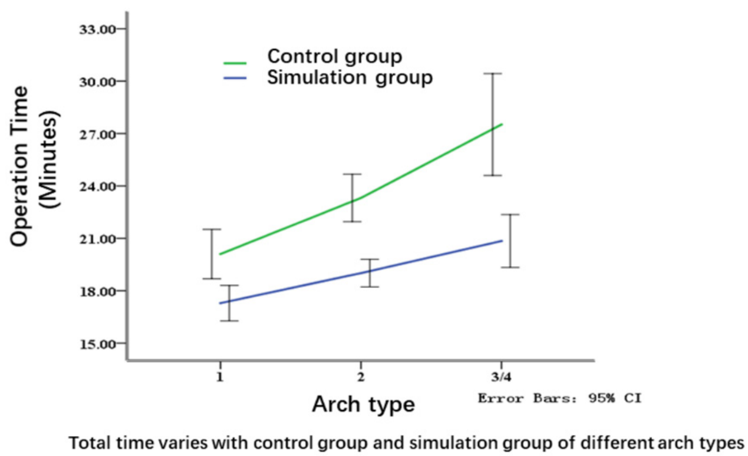


**Figure 3.** Variance in the operation time of simulation group and control group for different arch types.

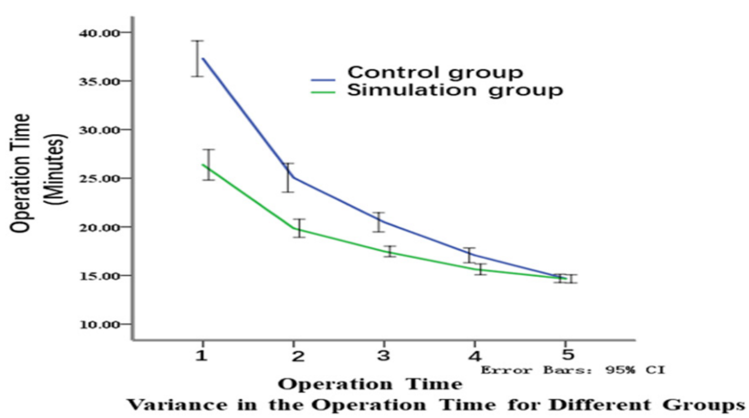


**Figure 4.** Variance in the operation time for different groups.

mastery of steps for the more difficult arch types III/IV operations.

*Variance in the operation time for different groups*

According to **Figure 4**, different groups and different time segments have statistical differences in interaction, supporting the facts that at the initial stage, the simulation group took less time than the control group, and its curve drops more smoothly as the number of operations increases. In later stages (Time Segment 5), both curves gradually approach and merge when the two groups are basically close in total time.

*$R^2$, K and B for Different trainees, relations amongst the average operation time, operation of simulator ΔY' and number of operations ΔX for simulation group and control group*

VI. Inflection points on the curve were found by curve fitting and secondary derivation: each trainee's operation time and number of operations were secondarily derived to obtain the corresponding X value in parallel with derivation. By substituting X, k and B (**Table 5**) into the formula Y=kln(X)+B, Y was found of approaching 0, and X shall be the inflection point on the curve (learning curve) (**Figure 5**). For simulation group and control group, the inflection points were 30.12 ± 3.54 and 42.67 ± 1.86 respectively. By the same method, the curve inflection point of trainees from simulation group using simulator was 32.83 ± 3.87.

## Discussion

Neural intervention operation requires a skillful operator. Beginners have to gone through three stages of exploration, practicing and stereotyping to master the technology and enter the steady phase [10]. Influencing factors include trainees' experience in interventional operations, anatomical knowledge, vascular anatomic variations, understanding of the operation, operation teamwork, differences in their abilities to understand, and justified selection of cases, etc. Moreover, personal interests, application

**Table 5.** $R^2$, K and B for different trainees from different groups

| | Group Type | Trainee 1 | Trainee 2 | Trainee 3 | Trainee 4 | Trainee 5 | Trainee 6 |
|---|---|---|---|---|---|---|---|
| $R^2$ | Simulation group | 0.611 | 0.365 | 0.214 | 0.744 | 0.557 | 0.584 |
| | Control group | 0.630 | 0.740 | 0.753 | 0.747 | 0.795 | 0.685 |
| K | Simulation group | 35.239 | 31.556 | 27.279 | 35.694 | 34.275 | 32.597 |
| | Control group | 50.321 | 48.567 | 55.420 | 47.538 | 53.844 | 51.188 |
| B | Simulation group | -5.123 | -3.824 | -2.782 | -5.231 | -4.986 | -4.733 |
| | Control group | -8.696 | -8.398 | -10.058 | -8.166 | -9.737 | -8.828 |

The two groups had statistical difference in inflection points ($P < 0.01$) as the inflection point of simulation group occurred ahead of the control group.

prospect of the technology, support from competent hospital departments in the form of policies, hospital environment, operation apparatus and operation team will affect the learning curve to some extent. At present, studies have indicated that the use of vascular simulation not only helps improve the operation level of trainees as they practice more, but also improves the technical level of the whole operation team [5, 11-14]. Meanwhile, trainees have a chance to experience errors on the principle of non-maleficence [15], indirectly reducing iatrogenic events and complications of intervention operations [16-18], improving the rate after healing [5, 19], shortening patients' and operators' exposure to X-ray [5], and allowing trainees practicing anytime and anywhere. However, some training apparatuses are expensive and affordable only for large medical institutions at present, which restricts the popularization of intervention training.

At the initial stage of neural intervention training, trainees are arranged to observe intervention operations for more perceptual knowledge; after familiarizing with the basic operation processes, they then participate in intervention operation as an assistant to further master related anatomic structures, understand intervention operations, and obtain operation techniques and skills so that they know where they are; at the initial stage of independent intervention operations, tutors strictly comply with the principle of "free practice under supervision" to avoid any potential medical risks to a certain degree, eliminate stress on trainees [20], and provide them with some space for independent thinking. In the later stage of training, the learning curves gradually flatten and operation time fluctuates in a small range as trainees practice more in simulated operations and actual intervention operations, accumulate more experience and intervention knowledge, and become more skillful. Training follows the principle of familiarizing trainees with operation processes for intervention before transferring to them operation techniques and skills, and practicing with micro catheters and micro guide wires only after trainees can independently and sophisticatedly conduct neural intervention angiography, and intervention treatment being the last part.

3D printing technology makes the production and popularization of simulated operation training equipment characterized by high cost performance possible as it can be relied on to accurately make a high-biofidelity vascular model and efficiently simulate operation training. Based on this study, the main features of 3D printing technology are as follows:

1. It provides trainees a chance to familiarize themselves with the relevant operation processes of intervention operations and enter the steady phase of learning curve rapidly. Compared with traditional training methods, simulator training with 3D Printed Vascular Simulation System has trainees gathered for intensive study in a short time to eliminate restrictions of practicing chances, so that they can have an intimate knowledge of information relevant to anatomy of blood vessels in neural intervention and the intervention process, advancing rules, status and operation techniques of catheter and guide wire from a 3D perspective rapidly and intuitively, mastering actual intervention operations faster.

2. It allows trainees to adapt to operative procedures faster and master the techniques and processes for angiography rapidly and independently at the clinical operation stage via simulated operation training. Their familiarization

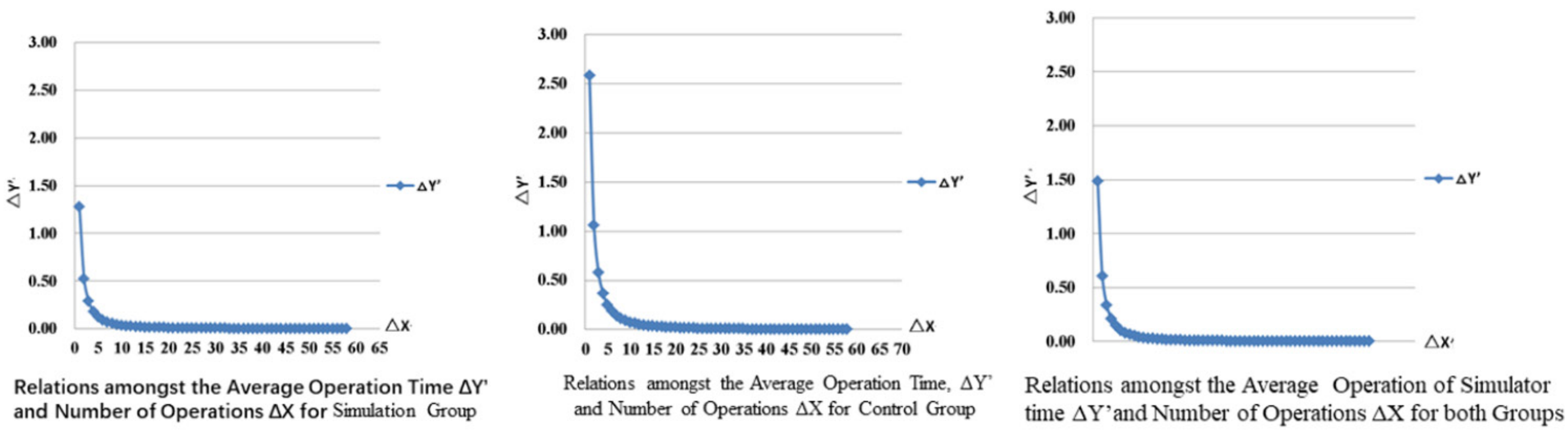


**Figure 5.** Relations amongst the average operation time, operation of simulator ΔY' and number of operations ΔX for simulation group and control group.

with the processes and techniques of intervention operation at the initial stage to a certain degree assure calmness and cooperation during operations with less utile actions, cuts down on the time required for operation and puncturing, improves the capacity to understand, and help trainees enter the steady phase of learning curve in advance. Practicing with simulator accelerates the progress to steady phase of simulated operations and shortens the time of steady interval compared with actual operation procedures, which may be attributed to following reasons: simulator is an inanimate *in vitro* vascular model which is relatively stable in arch type and varies little so that trainees can adapt quickly to them; in simulated training, trainees often find it difficlut to immense themselves in the atmosphere, have less mental pressure and fewer considerations than in the operation, which result in their faster action than in an actual operation. Moreover, in actual operations, after each successful subtraction, the patient's conditions will be analyzed before the next step of angiography. In general, those factors contribute to a shorter total learning time with a simulator as a whole.

3. It reduces the incidences of surgery-related and intervention operation-related complications during training, pain, fears, and even body injuries to patients due to repeated operations. Cerebral angiography is the most basic but important procedure in neural intervention operations, during which, no complication is tolerable to doctors and patients. Regardless of its extremely high potential for medical risks, cerebral angiography is a major procedure and a challenge to all interventionists who have to experience and undertake it. Therefore, reducing the incidence of complications at this stage is important to doctors and patients, which may ultimately depend on proper simulated operation training. 4. Compared with learning of arch types I and II, 3D simulated system training plays a significant improving role in arch type II and horn aortic arch that the latter two, and can be better mastered than the first two.

5. Current 3D printing simulator is not perfect because of its poor compliance due to the catheter wall which is harder than real human blood vessels. According to the working principle of a 3D printer, a simulator is built with layers of photosensitive resins featuring high biofidelity, but it fails to completely replicate the fine veins after formation (transverse veins vertical to the vertical axis of blood vessel), which results in a friction higher than that in an actual operation as the catheter or guide wire advances forward during operations, and creates difficulties in sliding a catheter or guide wire. Meanwhile, increased friction will also lead to higher difficulties in advancing of the catheter or guide wire.

Looking into the future, a 3D simulation system will look more into improving biofidelity and expanding the scope of applications to improve the medical training curriculum such as cardiovascular intervention, simulation of operations in cavities or tracts as a way to achieve higher teaching quality of simulated training. Furthermore, a 3D simulation system can be applied for transfer and verification of some new innovative or classical technologies in new areas to avoid irreversible injury or complications due to high-risk and high-difficulty operations. 3D printing is expected to be extensively applied in other branches of medical science or other fields, making greater contributions to the health and wellbeing of human beings. In addition, as a milestone achievement in medical education, simulation training with a simulator will be a powerful training tool undoubtedly to standardize and objectify skill assessment [21], and to be applied in qualification, promotion and professional title examinations of neural interventions [2]. It must be included as a compulsory course for medical science in the near future [3].

**Acknowledgements**

This work was supported by the Science and Technology Fund Project of Guizhou Health and Family Planning Commission and supported by the "Program for Innovative Research Team" of the Ministry of Education, the P. R. China.

**Disclosure of conflict of interest**

None.

**Address correspondence to:** Xin Xiang, Department of Neurosurgery, Affiliated Hospital of Guizhou Medical University, No. 28 Guiyi Street, Guiyang 550001, Guizhou, China. Tel: +86-15180747637; E-mail: pw3314e0@163.com

## References


[1] Chen GC, Lin CH, Li CM, Hsieh KS, Du YC and Chen T. Virtual-reality simulator system for double interventional cardiac catheterization using fractional-order vascular access tracker and haptic force producer. ScientificWorldJournal 2015; 2015: 697569.

[2] Chetlen AL, Mendiratta-Lala M, Probyn L, Auffermann WF, DeBenedectis CM, Marko J, Pua BB, Sato TS, Little BP and Dell CM. Conventional medical education and the history of simulation in radiology. Acad Radiol 2015; 22: 1252-1267.

[3] Ahmed K, Keeling AN, Fakhry M, Ashrafian H, Aggarwal R, Naughton PA, Darzi A, Cheshire N, Athanasiou T and Hamady M. Role of virtual reality simulation in teaching and assessing technical skills in endovascular intervention. J Vasc Interv Radiol 2010; 21: 55-66.

[4] Liu FY, Wang MQ, Fan QS, Feng D, Lin Z, Peng S, Yan W, Yan JY and Kai Y. The application of vascular interventional simulator ANGIO mentor in training interventional refresher physicians. J Interv Radiol 2013; 116: 767-782.

[5] Schimmel DR, Sweis R, Cohen ER, Davidson C and Wayne DB. Targeting clinical outcomes: endovascular simulation improves diagnostic coronary angiography skills. Catheter Cardiovasc Interv 2016; 87: 383-388.

[6] Widmer LW, Schmidli J, Widmer MK and Wyss TR. Simulation in vascular access surgery training. J Vasc Access 2015; 16 Suppl 9: S121-5.

[7] Wang D, Li T, Zhang Y and Hou J. Survey on multisensory feedback virtual reality dental training systems. Eur J Dent Educ 2016; 20: 248-260.

[8] Rudarakanchana N, Van IH, Desender L and Cheshire N. Virtual reality simulation for the optimization of endovascular procedures: current perspectives. Vasc Health Risk Manag 2015; 11: 195-202.

[9] Haery C, Koul S and Bhatt DL. Indications for carotid artery stenting. In: editors. Handbook of complex percutaneous carotid intervention: Springer; 2007. pp. 111-127.

[10] Moore MJ and Bennett CL. The learning curve for laparoscopic cholecystectomy. Am J Surg 1995; 170: 55-59.

[11] Bagai A. O Brien S, Al Lawati H, Goyal P, Ball W, Grantcharov T and Fam N. Mentored simulation training improves procedural skills in cardiac catheterization: a randomized, controlled pilot study. Circ Cardiovasc Interv 2012; 5: 672-679.

[12] Ericsson KA. An expert-performance perspective of research on medical expertise: the study of clinical performance. Med Educ 2007; 41: 1124-1130.

[13] Jensen UJ, Jensen J, Olivecrona GK, Ahlberg G and Tornvall P. Technical skills assessment in a coronary angiography simulator for construct validation. Simul Healthc 2013; 8: 324-328.

[14] Lipner RS, Messenger JC, Kangilaski R, Baim DS, Holmes DR Jr, Williams DO and King SB 3rd. A technical and cognitive skills evaluation of performance in interventional cardiology procedures using medical simulation. Simul Healthc 2010; 5: 65-74.

[15] Brewin J, Ahmed K and Challacombe B. An update and review of simulation in urological training. Int J Surg 2014; 12: 103-108.

[16] Barsuk JH, Cohen ER, Feinglass J, McGaghie WC and Wayne DB. Clinical outcomes after bedside and interventional radiology paracentesis procedures. Am J Med 2013; 126: 349-356.

[17] Barsuk JH, Cohen ER, Feinglass J, McGaghie WC and Wayne DB. Use of simulation-based education to reduce catheter-related bloodstream infections. Arch Intern Med 2009; 169: 1420-1423.

[18] Bruyere F, Leroux C, Brunereau L and Lermusiaux P. Rapid prototyping model for percutaneous nephrolithotomy training. J Endourol 2008; 22: 91-96.

[19] McGaghie WC, Issenberg SB, Barsuk JH and Wayne DB. A critical review of simulation-based mastery learning with translational outcomes. Med Educ 2014; 48: 375-385.

[20] Petri N, Toenissen C, Jens P, Petri H, Stoerk S and Voelker W. Does simulation-based training improve the proficiency of beginners in interventional cardiology? A stratified randomized study. J Am Coll Cardiol 2013; 61: E2039.

[21] Johnson SJ, Guediri SM, Kilkenny C and Clough PJ. Development and validation of a virtual reality simulator: human factors input to interventional radiology training. Hum Factors 2011; 53: 612-25.