

Development and Efficacy Evaluation of a Novel Arm Simulator and Synthetic Blood for Venipuncture Training among Health Science Students

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Research Article

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Abstract

Background

Venipuncture is an essential skill for health science students, but many struggle to learn because they lack realistic equipment for practice. The objective of this study was to develop an arm simulator and synthetic blood with physical features similar to human anatomy to enhance student learning.

Methods

The arm simulator uses natural latex to create flexible and durable skin over medical rubber tubes that simulate the median cubital, cephalic, and basilic veins. The system also includes a touch-screen pump to control blood flow and is designed to be easy to wash after use. The synthetic blood color #660808 was adjusted using red food coloring powder, red yeast rice powder, and coffee. This mixture was then combined with xanthan gum and glycerin to match the viscosity and density of human blood.

Results

According to our tests, the best mix of synthetic blood was formula 3, which had a viscosity of 4.11 cP, a specific gravity of 1.059, and a density of 1.052 g/mL. These values closely resemble those found in human blood. We tested the efficiency of the arm simulator and synthetic blood with 60 Medical Technology students. The results showed a very high level of reliability with a Cronbach's alpha (α) of 0.946. Senior students performed significantly better than junior students with a p -value less than 0.05, showing that the model effectively tracks skill growth. The students were notably satisfied with the training set, especially for its realistic appearance.

Conclusion

This developed arm simulator and synthetic blood set is highly effective and ready to be used as a primary teaching tool.

Trial registration:

TCTR20260726009 (registered on 26/07/2026); retrospectively registered;
<https://www.thaiclinicaltrials.org/show/TCTR20260726009>.

Background

Learning how to draw blood or venipuncture is one of the most important basic skills for students in the health sciences, especially for Medical Technology students who will spend their future working in laboratories. This skill is not only about putting a needle into a vein, but it also requires a high level of precision, anatomical knowledge, and professional care to ensure that the process is safe for the patient. If a student does not have enough skill or experience, it can lead to many problems such as causing serious pain, creating big bruises or hematomas, or getting a blood sample that is poor in quality and cannot be used for testing [1]. In the past, students used to practice on one another or on real patients; however, this practice has become increasingly problematic due to safety and ethics. Beginners often have shaky hands and lack confidence, which makes the patient feel very scared and stressed during the procedure. Moreover, there are now extremely strict rules about patient rights and medical ethics that prevent schools from letting untrained students practice on real humans [2]. This is why arm simulators are greatly necessary as a teaching tool because they provide a safe environment for students to learn the correct steps and build their confidence before they ever touch a real person. Using these models helps reduce the risk of injury and allows students to repeat the practice as many times as they need until they feel ready to work in a real hospital or clinic. Repeated practice is essential for developing procedural competence and confidence [3–5]. When students feel confident with the arm simulator, they are less likely to experience anxiety when they meet a real patient for the first time [6]. This confidence is immensely important because if the student is nervous, the patient will feel it

too. Good training also helps students understand where the veins are located and how deep they should put the needle. All these things together help make the student a good professional in the future who can take care of people well and safely [7].

Even though arm simulators are very common in many universities today, there are still many big problems that make the training not as effective as it should be. The biggest issue that we found in the laboratories is the quality of the synthetic blood used with these arm simulators. In many cases, teachers and students use basic mixtures like plain water mixed with red food coloring or even a Thai herbal drink called Uthai Thip to represent human blood. This is a major problem because these liquids are very different from real blood in terms of their physical properties. Human blood has a specific thickness and weight that simple water-based mixtures cannot match [8]. When students practice with these low-quality fluids, they do not get a realistic feeling of the blood coming back into the needle when they hit the vein. This lack of realism can make students misunderstand how the procedure really feels [9–10]. Another big problem is the material of the arm simulator itself. Many simulators bought from shops do not feel like real human skin. Some are too hard and some are too soft, which makes it difficult for students to learn how to find the veins correctly [11–12]. Additionally, many of these simulators break very easily after only a few students use them. The skin starts to have many holes and the internal tubes start to leak, which means the university must spend a lot of money to fix them or buy new ones [13–15]. The veins inside the models are often too easy to find, which is not like real life because real people have different types of veins. These problems show that the tools we have now are not good enough to prepare our students for the real work in hospitals. There is a need for something better that feels more like a real human arm and has blood that acts like real human blood [4].

To address these challenges, the objective of this study was to develop a more realistic arm simulator and a high-quality synthetic blood that closely matches the physical properties of human blood. We decided to solve this problem by focusing on the materials used for both the arm and the liquid to make the practice feel more real. For the arm simulator, we used natural latex to make the skin because it is flexible and strong. This skin can stay good even after many students poke it with needles. Inside the arm, we used medical rubber tubes and put them in the same places as real human veins like the median cubital, cephalic, and basilic veins. We also added a touch screen pump to control how the blood flows, so it feels like there is real pressure inside the arm. For the synthetic blood, we wanted it to look and feel real, so we used a mix of red food coloring powder, red yeast rice powder, and coffee to get the right color. Then, we added xanthan gum and glycerin to make it thick and heavy just like real human blood. We hoped that by making these instruments, students would have a better way to practice. We expected that after using our new arm simulator and synthetic blood, students would feel more satisfied and their skills would improve faster. Our goal was to make a training tool that is not too expensive but works effectively. This would help our students be ready for their jobs without the university having to buy very expensive equipment from other countries. We believe that if students have good tools to practice with, they will become better medical technologists who can give the best care to their patients. This project is our way to help improve medical education and make sure our students are the best they can be.

Methods

Design and development of the arm simulator

The arm simulator was designed and custom-built through the services of Department of Anatomy, Faculty of Medicine, Chulalongkorn University using natural liquid latex to create a skin layer that closely resembles the texture and feel of human skin, selected for its high elasticity and durability during repeated needle insertions. To simulate the venous system, medical-grade plastic tubing with a smooth surface was utilized to allow the latex to adhere effectively, creating a realistic representation of blood vessels situated beneath the skin layer. The simulator incorporates three primary veins of the arm: the median cubital vein, the cephalic vein, and the basilic vein. (Fig. 1A). To provide a realistic training experience, a simulated blood circulation system was manufactured to our specifications by College of Biomedical Engineering, Rangsit University and integrated to maintain flow and pressure similar to the human body. This system consists of a 1 L chamber for storing the synthetic blood, with a valve controlling the fluid entry into the pump. The pump circulates the synthetic blood through the arm simulator and back into the chamber in a continuous loop. A power supply provides energy to the pump, while a touch screen flow rate controller is used to precisely regulate the circulation speed, ensuring the internal pressure remains consistent for venipuncture practice (Fig. 1B).

Optimization of synthetic blood color

The development of the synthetic blood color was based on an initial reference formula consisting of 0.4 g of red food coloring powder and 0.6 g of cocoa powder dissolved in 100 mL of distilled water. To achieve the most realistic appearance, ten different trial formulations were further developed by varying the amounts of three primary coloring agents in 100 mL of distilled water. In all ten formulas, the amount of red food coloring powder was kept constant at 0.4 g. The primary variations involved adjusting the amounts of instant coffee powder and red yeast rice powder. Formulas 1 to 5 used a constant 0.1 g of red yeast rice powder while the instant coffee powder was increased in increments of 0.1 g, specifically at 0.1, 0.2, 0.3, 0.4, and 0.5 g. In Formulas 6 to 10, the amount of red yeast rice powder was increased to 0.2 g, while the instant coffee powder was again varied at 0.1, 0.2, 0.3, 0.4, and 0.5 g (Table 1). Each ingredient was accurately measured using a 2-decimal place digital scale. This systematic variation allowed for a detailed comparison to find the optimal balance between the red base, biological opacity, and the dark tone characteristic of human venous blood.

Table 1
Colorimetric analysis results of ten synthetic blood formulas with varying concentrations of red food coloring powder, instant coffee powder, and red yeast rice powder.

Formula	Red food coloring powder (g)	Red yeast rice powder (g)	Instant coffee powder (g)	Hex code
1	0.4	0.1	0.1	#be0001
2	0.4	0.1	0.2	#a40002
3	0.4	0.1	0.3	#900201
4	0.4	0.1	0.4	#480909
5	0.4	0.1	0.5	#5f0100
6	0.4	0.2	0.1	#9e0000
7	0.4	0.2	0.2	#660808
8	0.4	0.2	0.3	#580001
9	0.4	0.2	0.4	#480909
10	0.4	0.2	0.5	#2d0409

Development of synthetic blood viscosity and density

After the optimal color formula was selected, the physical properties of the synthetic blood, specifically viscosity and specific gravity, were further optimized through 12 different formulations, each adjusted to a final volume of 100 mL using distilled water. The optimization process was divided into two experimental sets. Formulas 1, 2, 3, 4, 5, and 6 involved varying the amount of glycerin at 0, 10, 20, 30, 35, and 40 mL, while maintaining xanthan gum at 0.02 g. Formulas 7, 8, 9, 10, 11, and 12 involved varying xanthan gum at 0, 0.01, 0.02, 0.03, 0.04, and 0.05 g, while keeping glycerin constant at 20 mL (Table 2). The preparation began by mixing xanthan gum with distilled water and glycerin using a magnetic hotplate stirrer for 20 minutes. The mixture was then allowed to rest at room temperature for 48 hours to ensure full hydration and stable viscosity of the xanthan gum. Subsequently, the coloring agents, consisting of 0.4 g of red food coloring, 0.2 g of instant coffee powder, and 0.2 g of red yeast rice powder, were added along with 0.1 g of sodium benzoate as a preservative. The final mixture was stirred for 15 minutes and then processed using a homogenizer for 10 minutes to achieve a uniform texture. The physical characteristics of each formula were then evaluated, including specific gravity measurement using a pycnometer and viscosity measurement using a viscometer, to identify the formula that best matches the properties of real human blood.

Based on previous reports, human blood at 37°C has viscosity at $\approx 3.5\text{--}5.5$ cP and density at $\approx 1.043\text{--}1.060$ g/mL. To pinpoint the formula that best mimics standard human blood, a ranking system was applied using a Normalized Score to measure the distance from target midpoints, specifically a viscosity of 4.50 cP and a density of 1.055 g/mL of human blood standard. The calculation was performed using the following formula (Fig. 2).

Table 2

Physical properties of the twelve synthetic blood formulas with varying concentrations of xanthan gum and glycerin.

Formula	Xanthan gum (g)	Glycerin (mL)	Viscosity (cP)	Specific Gravity	Density (g/mL)	Normalized Score
1	0	0	1.35 ± 0.04	1.003 ± 0.002	0.996	2.29
2	0.02	10	3.48 ± 0.12	1.033 ± 0.003	1.026	0.92
3	0.02	20	4.11 ± 0.09	1.059 ± 0.001	1.052	0.23
4	0.02	30	5.22 ± 0.15	1.090 ± 0.004	1.083	0.81
5	0.02	35	6.48 ± 0.21	1.108 ± 0.002	1.101	1.59
6	0.02	40	8.28 ± 0.18	1.121 ± 0.003	1.113	2.55
7	0	20	2.25 ± 0.07	1.061 ± 0.002	1.054	1.25
8	0.01	20	3.36 ± 0.11	1.059 ± 0.001	1.052	0.64
9	0.02	20	4.02 ± 0.13	1.063 ± 0.005	1.056	0.27
10	0.03	20	5.07 ± 0.16	1.062 ± 0.002	1.055	0.32
11	0.04	20	5.85 ± 0.19	1.063 ± 0.004	1.056	0.75
12	0.05	20	6.96 ± 0.22	1.062 ± 0.003	1.055	1.37

Measurement of viscosity, specific gravity, density, and stability testing

The physical properties of each synthetic blood formulation were evaluated using standardized laboratory procedures. The viscosity was measured using a viscometer attached with a spindle size 16S. The speed was adjusted to a suitable rotation level for each sample, and the viscosity values were recorded in centipoise (cP) once the readings reached a stable equilibrium. For specific gravity and density measurements, a pycnometer was utilized. Before testing, both the pycnometer and the synthetic blood samples were pre-warmed in a water bath at 37°C. The mass of the empty pycnometer was first weighed and recorded as M1. Then, distilled water at 37°C was filled into the pycnometer, ensuring all air bubbles were removed before sealing with the stopper and wiping dry. The mass of the water-filled pycnometer was recorded as M2. After cleaning and drying the pycnometer, the process was repeated using the pre-warmed synthetic blood sample, and the mass was recorded as M3. The specific gravity (SG) was calculated using the formula $SG = (M3 - M1)/(M2 - M1)$, and the density was subsequently determined by multiplying the SG with the density of water at 37°C ($\rho_{\text{sample}} = SG \times \rho_{\text{water}}$). All measurements were conducted to identify the formulation that most closely matched the physiological parameters of human blood. Finally, we tested the stability of all formulas by keeping them in sealed containers for 7 days at room temperature. We observed the samples daily to check for any color changes, sediment at the bottom, or separation of the ingredients to ensure the synthetic blood remained high-quality for use in the arm simulator.

Research participants

The study targeted a total population of 677 undergraduate students from the Faculty of Medical Technology at Rangsit University (as of October 10, 2025). This population included 168 Year 1, 142 Year 2, 153 Year 3, and 214 Year 4 students. Participants were categorized into two groups based on their clinical experience: those without prior venipuncture experience (Years 1 and 2 students) and those with prior experience (Years 3 and 4 students). Sample size calculation was performed using G*Power 3.1 software, which initially indicated a required sample of 60 participants (15 per year level) to achieve a Cohen's f effect size of 0.35 with a power of 0.75 to 0.80. The participant demographic was distributed as follows: 28.3% from Year 1 ($n = 17$), 21.7% from Year 2 ($n = 13$), 13.3% from Year 3 ($n = 8$), and 36.7% from Year 4 ($n = 22$).

Evaluation tools

The evaluation was conducted using 3 validated instruments, both verified for content validity by experts with an Index of Item-Objective Congruence (IOC) of 1.00. The first tool was a comparative colorimetric survey, which asked the participants about the

realism of the synthetic blood and Uthai Thip solution compared to real blood. The second tool was a 10-item technical performance checklist (OSCE style) used to assess practical skills, including equipment usage, patient positioning, tourniquet application, vein selection, site disinfection, needle placement, blood aspiration, needle withdrawal, needle disposal, and post-procedural care. The third tool was a satisfaction questionnaire, which assessed two main dimensions: design satisfaction (Arm realism, vein realism, blood realism, and convenience) and functional satisfaction (Perceived benefit, confidence gained, educational suitability, and overall satisfaction). Each item was rated across five distinct levels: 1 (Lowest/Very Dissatisfied), 2 (Less/Dissatisfied), 3 (Moderate/Neutral), 4 (Good/Satisfied), and 5 (Highest/Very Satisfied). All results were analyzed to compare the effectiveness of the training tools across the different groups of participants. The details regarding the comparative colorimetric survey, the technical performance checklist, and the satisfaction questionnaire administered via Google Forms are provided in the [Supplementary material 1].

Educational implementation

Before participating in the study, all 60 undergraduate students from the Department of Medical Technology provided their informed consent by signing a formal participation agreement. The process began with the evaluation of the physical appearance of the synthetic blood to ensure it met clinical training standards. Each student was presented with three blood collection tubes for a side-by-side comparison: containing 5 mL of real human venous blood, 5 mL of developed synthetic blood, and 5 mL of Uthai Thip dissolved solution placed under controlled cool-white fluorescent lighting. Students were assigned to observe the samples from three perspectives, including viewing the tubes against a white background to check the red color tone, swirling the tubes to check the opacity and how the fluid coated the glass wall, and observing the color of the fluid while being drawn into a clear plastic syringe. They then recorded their satisfaction scores using a 5-point Likert scale. After finishing the color evaluation, all students attended a pre-training session, which included a lecture on arm anatomy to identify the median cubital, cephalic, and basilic veins, and learned the standard operating procedures (SOP) for blood collection. This was followed by a technical demonstration where the instructor showed how to palpate the veins through the latex skin and how to monitor the blood flashback. For the hands-on practice, each student performed the procedure at an arm simulator station, using 70% alcohol for site preparation and inserting the needle at a 20-degree angle while the touch screen pump maintained realistic venous pressure. Instructors used a standardized checklist to verify if each student could successfully achieve a blood flashback within 3 attempts and students rated their own confidence using the form. Once the evaluation was complete, the arm simulator units were maintained by flushing the internal system with 1,000 mL of clean water and disinfecting the external surfaces with 70% alcohol.

Statistical analysis

Statistical analysis reported results as mean $\pm$ standard deviation (*SD*) or median with interquartile range (*IQR*). To compare performance across the four academic year levels (Years 1, 2, 3, and 4), Kruskal-Wallis tests or ANOVA were utilized, while secondary comparisons between the inexperienced group (combined Years 1 and 2) and the experienced group (combined Years 3 and 4) used the Mann-Whitney U test. Effect sizes included η^2 , ω^2 , ε^2 , and Cliff's delta (δ) with 95% confidence intervals (95% CI). Relationships were analyzed using two-tailed Spearman's rho (ρ). The internal consistency was verified using Cronbach's α , with acceptable reliability set at $\alpha \geq 0.70$ and good consistency at $\alpha \geq 0.80$. All statistical significance was set at $p < 0.05$. All analyses were performed using SPSS software.

Results

Evaluation of synthetic blood coloration via digital color mapping

Initially, we developed ten synthetic blood formulations by varying the amounts of instant coffee and red yeast rice powder to achieve a realistic appearance. The results showed that these two components directly dictated the digital color codes (Hex Codes) and the overall opacity of the samples. While instant coffee was used to reduce the brightness of the red food coloring, the addition of red yeast rice powder from 0.1 g to 0.2 g was essential for increasing the turbidity to match human blood characteristics. According to the color analysis in Fig. 3, formula 1–5 appeared too bright and translucent, with Hex Codes of #be0001, #a40002, #900201, #480909, and #5f0100, respectively. Although the red yeast rice powder was increased to 0.2 g in the second group, in the second group, formula 6 still appeared slightly bright with a Hex Code of #9e0000. On the other hand, formula 8–10 produced dark

brownish shades with Hex Codes of #580001, #480909, and #2d0409, respectively, which did not represent fresh blood. We found that formula 7, containing 0.4 g red food coloring, 0.2 g instant coffee, and 0.2 g red yeast rice powder, provided the most appropriate Hex Code of #660808 (Table 1). This specific shade closely resembles human venous blood and received the highest satisfaction score from 60 medical technology students at 4.52 ± 0.54 (90.40%), which is much higher than the Uthai Thip solution at 2.70 ± 1.42 (54.00%) (Fig. 4). After the freeze-drying and reconstitution process, the color of formula 7 remained stable at #660808 with no precipitation, proving it can be used effectively for the fabrication of simulator testing and training applications.

Physical property analysis toward optimization of synthetic blood formula

The experimental results for the physical properties of all twelve synthetic blood formula were determined through two distinct testing phases: varying the concentration of glycerin and varying the concentration of xanthan gum. In the first group (Formula 1–6), xanthan gum was held constant at 0.02 g, while the volume of glycerin was incrementally increased from 0 mL to 40 mL. The second group (Formula 7–12) maintained a constant glycerin volume of 20 mL while varying the xanthan gum content from 0 g to 0.05 g. Data from these tests showed that formula 3, 4, 9, and 10 produced viscosity values that aligned with human physiological standards, while formula 3, 7, 8, 9, 10, 11, and 12 successfully met the criteria for both specific gravity and density. Within the normalized scoring framework, a lower value represents a closer proximity to the ideal human blood standard. The final optimization analysis revealed that formula 3 achieved the lowest score at 0.23, followed by formula 9 at 0.27 and formula 10 at 0.32. Based on these scores, formula 3 comprising 0.02 g of xanthan gum and 20 mL of glycerin is identified as the most effective model, demonstrating the highest physical fidelity for the fabrication of blood training simulator (Table 2).

Comprehensive evaluation of user satisfaction and functional fidelity

The developed venipuncture arm simulator and synthetic blood were subjected to a rigorous evaluation by 60 medical technology students, encompassing both pre-experienced individuals (Years 1 and 2, $n = 30$) and those with prior clinical experience (Years 3 and 4, $n = 30$). Regarding the physical attributes of the simulator, the realism of its form, color, and size of the arm simulator received a mean satisfaction score of 4.85, with 85% of participants ($n = 51$) was awarded the maximum 5 points. The anatomical realism of the veins was rated at 4.73, with 75% ($n = 45$) receiving a perfect score. The synthetic blood samples earned a mean score of 4.88, with 90% ($n = 54$) of users expressing the highest level of satisfaction. Similarly, the functional aspect, the ease of the venipuncture procedure achieved a mean score of 4.88, with 90% ($n = 54$) of participants rating it at 5 points. The educational utility of the system was particularly emphasized, achieving a perfect mean score of 5.00 (100%) for its benefit as a pre-clinical training tool. Furthermore, the simulator significantly enhanced student confidence, with a mean score of 4.83 (88.3%). The appropriateness of integrating this system into the teaching and learning curriculum was rated at 4.95, with 95% ($n = 57$) of respondents in full agreement. Ultimately, the overall satisfaction with the use of the arm simulator reached a perfect mean score of 5.00, with 100% of the participants ($n = 60$) was awarded the highest satisfaction rating (Table 3).

Table 3
Mean satisfaction scores and functional evaluation of the venipuncture arm simulator across different student years.

Student Year	Students number	Arm realistic	Vein realistic	Blood realistic	Convenient	Perceived benefit	Obtained confidence	Educational suitability	Overall satisfaction
1	17	4.88 ± 0.33	4.82 ± 0.53	5.00 ± 0.00	4.94 ± 0.24	5.00 ± 0.00	4.94 ± 0.24	4.94 ± 0.24	5.00 ± 0.00
2	13	4.77 ± 0.44	4.77 ± 0.44	4.92 ± 0.28	4.85 ± 0.38	5.00 ± 0.00	4.54 ± 0.88	4.92 ± 0.28	5.00 ± 0.00
3	8	5.00 ± 0.00	4.63 ± 0.52	4.88 ± 0.35	5.00 ± 0.00	5.00 ± 0.00	4.75 ± 0.46	5.00 ± 1.00	5.00 ± 0.00
4	22	4.82 ± 0.39	4.68 ± 0.48	4.77 ± 0.53	4.82 ± 0.50	5.00 ± 0.00	4.95 ± 0.21	4.95 ± 0.21	5.00 ± 0.00
1 and 2	30	4.83 ± 0.38	4.80 ± 0.48	4.97 ± 0.18	4.90 ± 0.31	5.00 ± 0.00	4.77 ± 0.63	4.93 ± 0.25	5.00 ± 0.00
3 and 4	30	4.87 ± 0.35	4.67 ± 0.48	4.80 ± 0.48	4.87 ± 0.43	5.00 ± 0.00	4.90 ± 0.31	4.97 ± 0.18	5.00 ± 0.00
Total	60	4.85 ± 0.36	4.73 ± 0.48	4.88 ± 0.37	4.88 ± 0.37	5.00 ± 0.00	4.83 ± 0.49	4.95 ± 0.22	5.00 ± 0.00

Instructor evaluation of venipuncture skills across academic years

The evaluation of students' venipuncture skills by instructors demonstrated significant differences in performance between academic levels across all ten categories. An independent samples t-test revealed that senior students in Years 3 and 4 achieved significantly higher competency scores compared to junior students in Years 1 and 2 ($p < 0.01$). Specifically, junior students (Years 1 and 2) exhibited greater score variance, with mean scores ranging from 4.23 to 4.57; their lowest performance was observed in patient positioning (4.23 ± 0.77) and needle placement (4.23 ± 0.68), while equipment usage yielded the highest score (4.57 ± 0.63). In contrast, senior students (Years 3 and 4) demonstrated a near-perfect mastery of skills, achieving the maximum possible score (5.00 ± 0.00) in five distinct categories: site disinfection, needle placement, needle withdrawal, needle disposal, and post-procedural care. The t-test confirmed that these senior scores were significantly higher than those of the junior group ($p < 0.001$). The only minor fluctuation within the senior cohort was observed in blood aspiration, which still maintained a high average of 4.87 ± 0.57 . Overall, the total mean scores across all 60 participants ranged from 4.58 to 4.76. These statistical results confirm that the developed simulator effectively reflects and differentiates clinical skill competencies based on the students' cumulative academic and practical experience (Fig. 5).

Statistical analysis of clinical skills and user satisfaction (Mann-Whitney U Test)

To further validate the results, a Mann-Whitney U test was used to compare the performance and satisfaction between the two groups of students. According to the technical performance checklist, the analysis confirmed that Years 3 and 4 students performed significantly better than Years 1 and 2 students, with a U value of 158 and a p-value of 3.96×10^{-6} . The effect size was large (Cliff's $\delta = 0.649$), indicating that Years 3 and 4 students had an approximately 82% higher probability of achieving better scores than the Years 1 and 2 group. In contrast, there was no significant difference between the two groups regarding their satisfaction with the arm simulator and synthetic blood ($U = 448, p = 0.986$). The effect size for satisfaction was negligible (Cliff's $\delta = 0.003$), showing that both experienced and inexperienced students were equally satisfied with the developed training materials. These statistical findings prove that while the simulator effectively measures clinical skill levels, it provides a high-quality and consistent learning experience for all users regardless of their seniority.

Correlation analysis and assessment tool reliability

We used Spearman's rank correlation to look at the relationship between student seniority and their performance. The results showed that the overall skill score had a significant positive correlation with the academic years from 1 to 4 ($\rho \approx 0.54, p < 0.001$), meaning that skills generally improve as students move to higher years. When comparing groups, the Years 3 and 4 group had a

stronger positive correlation with higher skill scores than the Years 1 and 2 group ($\rho \approx 0.60, p < 0.001$). Most of the 10 specific tasks in the technical performance checklist also showed a positive correlation with both academic years ($\rho \approx 0.54, p < 0.001$) and the senior student group ($\rho \approx 0.60, p < 0.001$). This was especially clear during the needle placement, needle withdrawal, needle disposal, and post-procedural care steps. For user satisfaction and realism across the 8 items, we did not find a significant correlation with seniority. This happened because of a "ceiling effect," as almost all students gave the maximum score of 5.00. To check the reliability of our assessment tools, we calculated Cronbach's α . The 10-item skill assessment showed excellent reliability at 0.946. However, the 8-item satisfaction scale had a lower α value of 0.495. This lower score is because the satisfaction ratings were so high and similar (the ceiling effect) that it became difficult to statistically show a difference between the groups.

Discussion

The development of this venipuncture arm simulator and synthetic blood shows very good results for both physical realism and training use. For the blood color, we found that using red yeast rice powder mixed with coffee is much better than using standard food colors like Uthai Thip. Our formulation gives a dark red color with a hex code of #660808, which closely resembles human venous blood, while other common colors often look too pinkish or bright. Having the right color is extremely important because it makes the "flashback" look real when students practice, and this visual feedback is a key part of learning how to draw blood correctly [14]. For the physical properties, we used a specific mix of xanthan gum and glycerin to control the viscosity and density of the liquid. Real human blood usually has a viscosity of 3.5–5.5 cP [16] and a specific gravity of 1.060, and a density of 1.055 g/mL [17], and by matching these values, our synthetic blood flows and reacts correctly during needle insertion. This provides a realistic feeling for the students, which many studies suggest is more important for their confidence than just how the arm model looks on the outside [18]. Our "High Fidelity at Low Cost" method allowed us to create a high-quality training tool without spending a lot of money on expensive commercial models that can be expensive. By using these natural ingredients, we can produce a large amount of realistic synthetic blood that is safe and effective for daily classroom use [14]. This approach ensures that all students have sufficient materials for repeated practice until competency is achieved with the procedure, which is often a problem when using expensive commercial kits that have limited supplies.

The combination of the realistic synthetic blood and the arm model is very effective for testing and distinguishing different skill levels among students. Our study showed clear significant differences in scores between junior students (Years 1 and 2) and senior students (Years 3 and 4) across all 10 clinical tasks, such as choosing the right vein, needle placement, and drawing the blood sample. For example, Year 1 students had an average needle placement skill score of 4.18, while Year 4 students reached a perfect score of 5.00. This significant difference ($p < 0.001$) and the strong correlation ($\rho \approx 0.54$ to 0.60) show that the model is a very good tool for measuring a student's actual experience level [19]. These results are actually better at showing skill gaps than some other homemade or 3D-printed models used in past research, which sometimes struggled to show clear differences between beginners and experts [3, 20]. Students also gave a very high satisfaction score for the realism of both the arm and the blood. This high rating suggests that the "pop" or the tactile feel when the needle hits the vein closely mimics real human tissue, which normally has a puncture force of about 0.64 N. Because the satisfaction scores were consistently high across all groups, it suggests that the model provides a realistic user experience and is useful to both beginners who are just starting and senior students who have already worked with real patients in the clinic. This feedback is crucial because it confirms that our low-cost model does not sacrifice quality for price, providing a professional-level experience that meets the needs of a modern medical technology curriculum [21].

For assessment and reliability, our tools proved to be high quality for medical education and met international standards. The 10-item skill assessment we used had an excellent reliability score with a Cronbach's α of 0.946, which is even higher than many international nursing and medical studies where α values typically range between 0.70 and 0.85 [22–23]. We did find a "ceiling effect" in the satisfaction scores because almost every student gave a perfect 5.00, which made the alpha score for that specific part look lower at 0.495. However, this is not a negative result; it actually means the simulator is very satisfying for the students and meets their high expectations. The large effect size (Cliff's $\delta = 0.649$) for the skill difference between the junior and senior groups further confirms that this model is a valid tool for tracking student progress over time. This level of validation is important because it meets international standards for patient safety and medical training efficiency. By proving that a student's score on our simulator matches their actual seniority, we can trust this tool to tell us when a student is ready for real-world clinical work. In conclusion, this study proves that we can create a locally developed, low-cost simulator that works just as well as, or even better than expensive commercial versions [14, 24]. It provides a sustainable and effective way to prepare the next generation of medical laboratory scientists for real-world clinical procedures while saving a significant amount of department budget.

Conclusion

In conclusion, this project successfully combined the development of a high-fidelity venipuncture arm model and synthetic blood that are both realistic and cost-effective. By using natural ingredients like red yeast rice powder and coffee, we achieved a specific dark red color (#660808) that is more accurate than standard food colorings, while the physical properties were controlled with xanthan gum and glycerin to match the viscosity of 3.5–5.5 cP and a specific gravity of 1.060, and a density of 1.055 g/mL. These features provide a realistic "flashback" and the correct tactile feel during needle insertion, which are essential for student training. When tested in real classes, the simulator was effective at showing differences in skill levels, as Years 3 and 4 students achieved significantly higher scores than Years 1 and 2 students ($p < 0.001$), with a strong positive correlation between seniority and performance ($\rho \approx 0.54$ to 0.60). Furthermore, the students gave a near-perfect satisfaction and realism score, confirming that the model closely replicates the feel of real human tissue, while the assessment tool showed high reliability with a Cronbach's α of 0.946. This locally developed innovation not only meets the international standards for patient safety and medical education but also provides a sustainable way for the department to reduce the high cost of importing training equipment from abroad.

Abbreviations

ANOVA Analysis of variance

cP Centipoise

δ Cliff's delta

f Cohen's effect size

CI Confidence intervals

α Cronbach's alpha

°C Degree Celsius

ρ (Unit) Density

η^2 Eta-squared

ε^2 Epsilon-squared

g Gram

g/mL Gram per milliliter

Hex Hexadecimal Color Codes

IQR Interquartile range

IOC Item-objective congruence

L Liter

mL Milliliter

OSCE Objective structured clinical examination

ω^2 Omega-squared

p -value Probability value

ρ (Statistic) Spearman's rho

SG Specific gravity

16S Spindle size 16

SD Standard deviation

SOP Standard operating procedures

SPSS Statistical Package for the Social Sciences

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Rangsit University (Approval No. RSUERB2024-058) before the commencement of the study. All methods were performed in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki, The Belmont Report, CIOMS Guideline, and International Conference on Harmonization in Good Clinical Practice or ICH-GCP. Institutional permission was granted by the relevant heads to access the participants. Written informed consent was obtained from all participants prior to their participation, following a detailed explanation of their rights, the voluntary nature of the study, and their right to withdraw at any time without penalty. Participant privacy and data confidentiality were maintained through the use of anonymous codes and secure data storage. Additionally, both the independent coder and the interviewer signed confidentiality agreements.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

Suranat Phonghanpot performed the experiments, analyzed the data, and was a major contributor in writing the manuscript. Faongchat Jarintanan conceived and supervised the project, provided methodological guidance, interpreted the data, critically revised the manuscript for important intellectual content, and served as the project advisor. All authors read and approved the final manuscript.

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Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

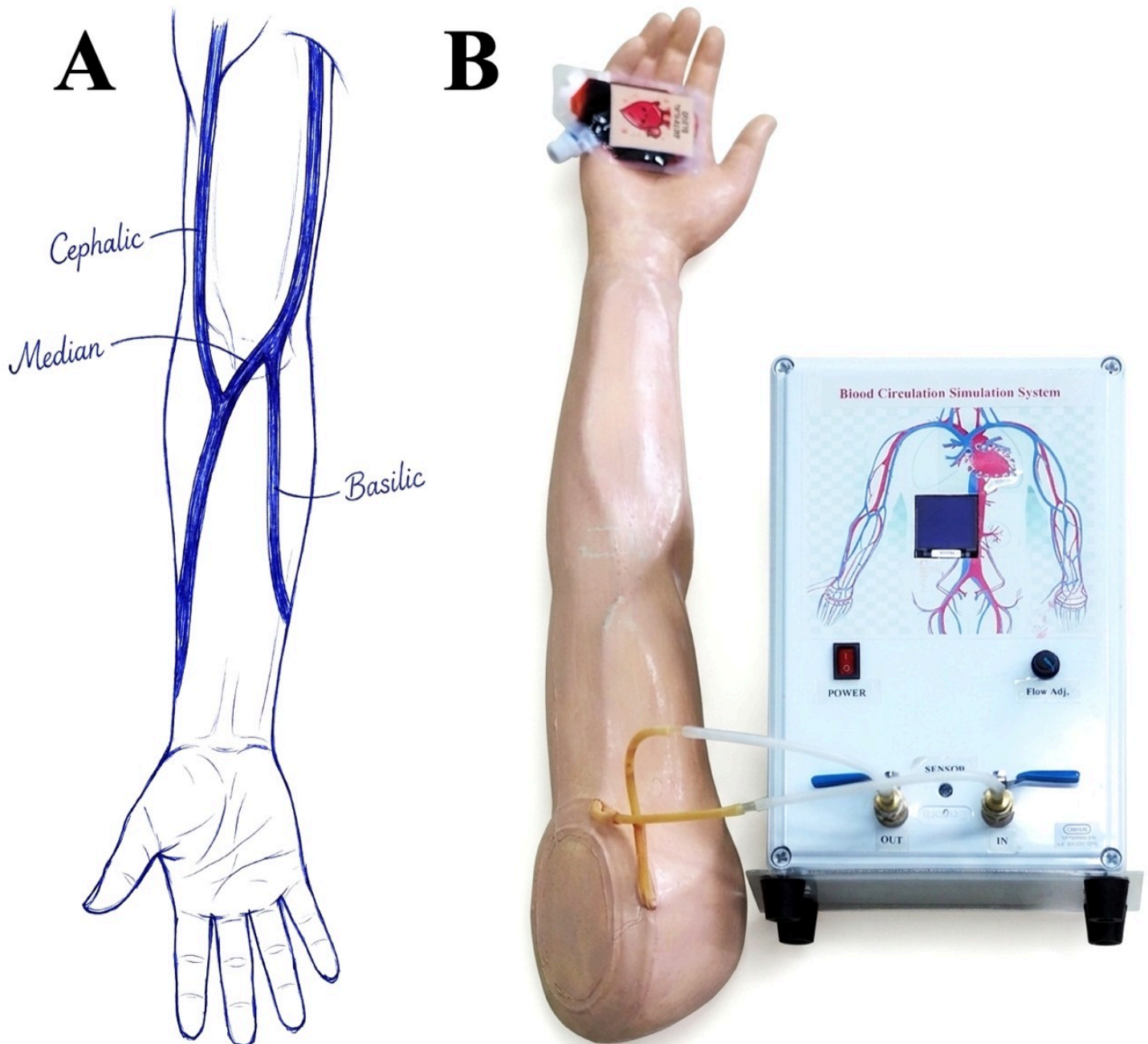


Figure 1

(A) The design of custom-built venipuncture arm simulator, showing the layout of the three primary veins: the median cubital, cephalic, and basilic veins. (B) The complete assembly of the developed venipuncture arm simulator connected to the blood circulation simulation system unit.

$$\text{Score} = \sqrt{\left(\frac{\text{Measured Viscosity} - 4.50}{5.50 - 3.50}\right)^2 + \left(\frac{\text{Measured Density} - 1.055}{1.060 - 1.043}\right)^2}$$

Figure 2

Formula used for calculating the normalized score to determine the closest match to standard human blood midpoints (viscosity of 4.50 cP and density of 1.055 g/mL).



Figure 3

Comparison of the ten synthetic blood formulas using under Hex Code digital color analysis.

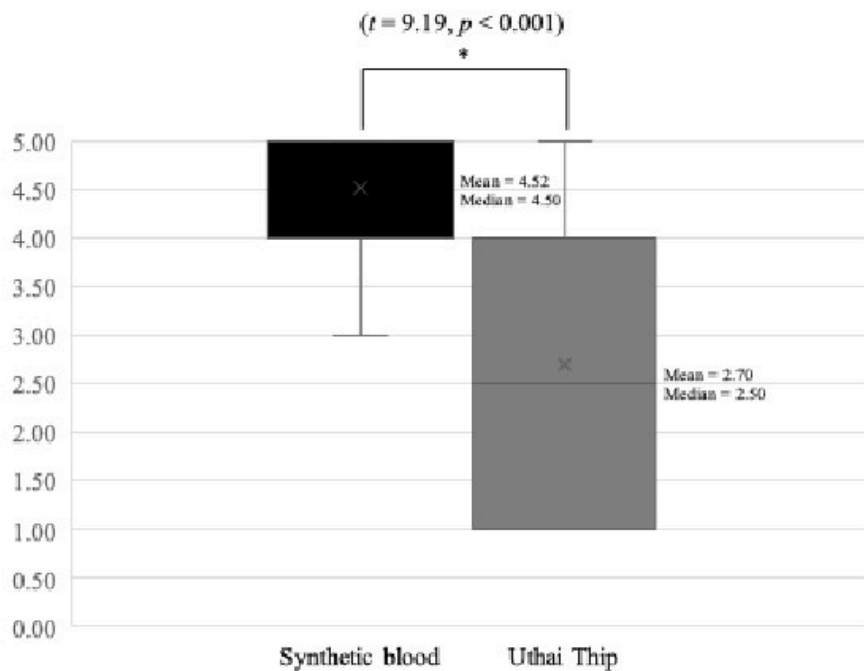


Figure 4

Comparison of satisfaction scores between the optimized synthetic blood (Formula 7) and Uthai Thip solution evaluated by 60 medical technology students. * The pair is statistically significant with $p < 0.001$.

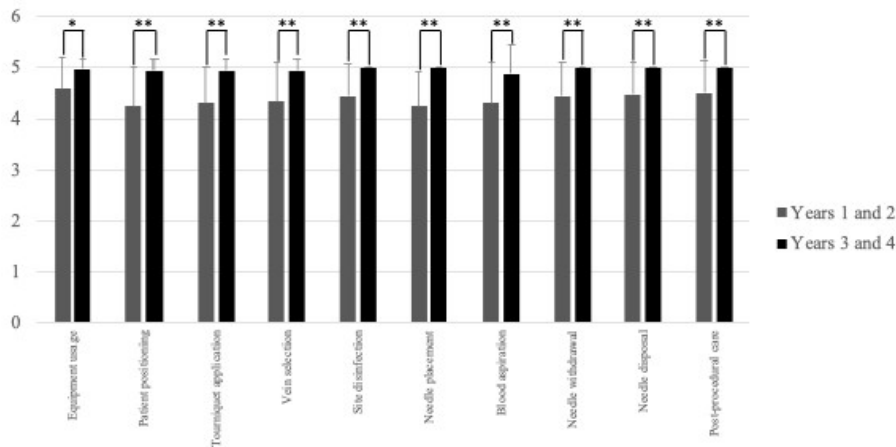


Figure 5

Comparison of performance scores between junior students (Years 1 and 2) and senior students (Years 3 and 4) across ten evaluation categories. * The pair is statistically significant with $p < 0.01$. ** The pair is statistically significant with $p < 0.001$.

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