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Phantoms for ultrasound-guided vascular access cannulation training: a narrative review

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Abstract

The objective of this paper is to review and compare the different commercial and homemade models of ultrasound-guided vascular cannulation phantoms, as well as the methods used for the elaboration of the latter. There are a variety of simulators for ultrasound-guided puncture techniques, from simple homemade phantoms to the most sophisticated and expensive virtual reality simulators. Commercial-grade ultrasound phantoms are expensive and although they are reusable, their cost can be a barrier to simulation-based training. Homemade phantoms are a cost-effective, highly useful tool for teaching vascular access using ultrasound. For the elaboration of the homemade ones, different substances and elements are usually used to produce varied echogenicities and geometries. Specifically, animal-based ones provide more realistic tissue feedback and have a background echogenicity that is closer to that of human tissue. A powerful alternative is the use of poly vinyl alcohol or modified mixtures of this material, which would be better suited to cannulation simulation with high functional fidelity.

Keywords: ultrasonography; training; phantoms; vessel; catheterization

Introduction

Ultrasound (US) has widely shown its great usefulness in facilitating diagnosis and optimizing therapeutic decisions in many medical specialties [1,2]. In addition, US enables us to guide interventional procedures, reducing the complications of invasive techniques [3].

The use of US at the bedside for vascular cannulation is a fairly current concept, the first publications of which date back to the early 1990s. The first studies focused on US-guided cannulation of the internal jugular vein and subclavian vein, but it quickly spread to any vascular access, whether arterial or venous [4,5]. In 2012, the first International Consensus Document on the use of US-guided vascular access cannulation was published [6], and the recommendation was to assess the vascular anatomy before performing the procedure to locate the most favorable vessel. This approach has proved to improve the success probability of the procedure itself as well as reduce the risk of potential complications. In addition, several studies have demonstrated a significant increase in the safety, efficacy, and efficiency of US-guided vascular access compared to anatomical landmark-guided cannulation [6,7].

Learning the skills that vascular interventional procedures require is a complex process, where it is necessary to have prior clinical training. Concern for minimizing complications with consequent patient safety improvement and cost reduction during the learning curve of invasive techniques has led to the use of simulators for the teaching-learning processes. This simulating-based

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training provides the opportunity to learn and practice technical skills in a safe, controlled, and reproducible educational setting [8].

Phantoms are artificially produced models that resemble human tissue by providing specific anatomy. Its use has proven to be a valuable training tool for US training and, particularly, for US-guided vascular cannulation, with the consequent increase in efficiency and reduction of insufficient or non-diagnostic blood samples [9]. There are a variety of simulators for US-guided puncture techniques, from simple homemade phantoms to the most sophisticated and expensive virtual reality simulators. The ideal simulator should be similar to human tissue, inexpensive, readily available, capable of repeated use, and, of course, not a health hazard. However, an ideal phantom for this application has not yet been developed [10]. Vascular simulation models for training in US-guided cannulation are synthetic or biological. Literature is available in both commercial and homemade, created with different materials and techniques such as gelatin, agar-agar (food products), and animal specimens such as chicken or turkey [11-15]. All these models must have tubular structures inside and be filled with a liquid resembling blood vessels. Cadaveric simulators are also used for US-guided procedures before patient care. However, due to their disadvantages, they are mostly used for anatomy learning

The objective of this paper is to review and compare the main available commercial and homemade models of US-guided vascular cannulation phantoms, as well as the methods used for the elaboration of the latter. For this reason, we carried out a literature search on the usefulness and application of homemade phantoms for learning US-guided vascular accessing the databases of Medline (Pubmed), Embase, Cochrane and Web of Knowledge and limited to articles in English language published in the last five years. In the search strategy the terms used were: ultrasound, ultrasonography, imaging phantoms, radiologic phantom, simulation training, vascular access devices, cannulation.

The results obtained from the literature review on the main phantoms used for training in US-guided procedures for vascular access are described in the following sections. Table I shows the main characteristic of the ideal phantoms for US-guided procedures for vascular access according to the literature search results.

Table I. Characteristics of the ideal phantoms for ultrasound-guided procedures for vascular access

• Reproduce the texture and strength of human tissue
• Inhibit lateral movement of the needle
• Have sufficient ultrasound penetration to allow the identification and location of targets down to a depth of 10 cm
• Be easily repairable, due to the damage caused by the insertion of the needle.
• Have targets that must be clearly distinguished from the surrounding medium on the ultrasound image
• Have targets that will not corrode over time
• Clearly identify the operator when contact has been made between the needle and the target
• Be easily accessible and affordable
• Have a long shelf life
• Have no infection problems
• Easily transportable
• Be composed of non-perishable material.
• Have different levels of difficulty/complexity that can be easily changed.
• Be easily reproducible in any medium

1. Commercial simulator

Commercial-grade US phantoms are expensive and although they are reusable, their high cost can be a barrier to their application in simulation-based training. Those designed for specific targets or a wide range of uses are available on the market [16]. Commercial simulators such as the CAE Healthcare Blue Phantom™ (Sarasota, FL) and the Kioto Kagaku CVC Insertion Simulator™ (Kyoto, Japan) are widely used. These are durable and can withstand dozens of needle insertions but cost between $1,000 and $5,000 each [17].

Specifically, the Branched 4 Vessel Vascular Access US Training Block Model™, manufactured by Blue Phantom, is a commercial simulator available as a training model. It allows obtaining images of bifurcated vessels, following the course of the vessels, and guiding the needles to the target vessel using US imaging. Its branching vessels offer multiple training opportunities such as independent linear vessels for initial training, plus multiple overlapping branching vessels for more advanced US-guided training [18]. However, it should be noted that one of its major disadvantages is that the path of the needle usually leaves a mark and, despite its cost, it tends to deteriorate after multiple punctures [19]. Table II lists the main advantages and disadvantages of the most commonly used phantoms, i.e., the Blue Phantom.

2. Homemade simulators

The high cost of commercial simulators has led to the exploration of alternatives, including cadavers and homemade alternatives using gelatin [20] or animal specimens [21]. For the elaboration of homemade phantoms, differ-

Table II. Advantages and disadvantages of the commercial simulators blue phantoms

BLUE PHANTOMS	
Advantages	Portable Realistic No infection Large surface area Long shelf life Reusable
Disadvantages	Expensive Additional destinations cannot be embedded Unrealistic muscular and vascular imaging Needle and trajectory marked after a number of uses Does not reproduce human tissue texture

ent materials are used to produce varied echogenicities and geometries. These materials, with their advantages and disadvantages, are described below and summarized in table III.

PVA-C & PVC

There are two types of vinyl or plastic-resins material with many uses in the modern world. Polyvinyl alcohol criogel (PVA-C) provides texture and elasticity properties similar to soft tissues and is easily customized at a low cost. The use of modified polyvinyl alcohol (PVC) for US phantoms was first proposed by Li et al [22], who used glass beads to increase echogenicity.

The resulting phantoms have high structural rigidity, indefinite longevity, and are more resistant to crack formation compared to agar- and gelatin-based phantoms [23,24]. As a tissue-mimicking material, its mechanical and imaging properties can be tuned to meet the needs of users. For example, hardness can be tailored by changing the ratio of softener to PVC polymer, introducing mineral oil to lubricate the needle insertion, and including glass beads to disperse acoustic energy similar to biological tissue [22]. In addition, the acoustic properties of PVA provide US images with echogenicities closer to those from humans [25].

Table III. The most common homemade simulators and their advantages and disadvantages

PHANTOMS	ADVANTAGES	DISADVANTAGES
Silicone PVC	No infection Portable Long half-life Flow identifiable on Doppler mode	Small working surface Expensive Marked path of the needle
Gelatin	Transportable Large area Injectable targets can be embedded Appearance and shape can be modified Transparency can be changed Easy construction Low cost	Preparation time Needle marking after each use Shelf life 2-3 weeks Uniform appearance Breaks due to excess pressure Does not reproduce human tissue texture Possibility of air artifacts in the vascular structure
Agar-Agar	Targets can be placed Difficulty level can be increased Portable	Growth and transmission of infection as an organic basis Not readily available Memory after each needle pass Preparation time
Animal Model (chicken, pork)	Realistic feel of human tissue Natural structures present, may be embedded Targets Muscle and vascular image fidelity Transportable Low cost Easy construction	Short shelf life Preparation time Less hygienic Infection Possibility of air artifacts in the vascular structure
Ham or mortadella	Affordable, readily available Easy to manufacture Low cost	Less hygienic Infection No anatomical references of any venous access
Tofu	Simple Affordable Portable Degree of complexity can be changed Target can be inserted but not canalized	Not readily available Decomposes under pressure Filter water over time Requires refrigeration Too uniform in sonographic appearance Infection

PVC: polyvinyl alcohol

Fig 1. Gelatin homemade phantom: a) container preparation; b) several plastic tubes are placed inside and then filled with liquid; c) holes of the container are then sealed with liquid glue; d) when the jelly solidifies, a layer of liquid latex is pureed in mimicking skin; e) result after 48 hours; f) after 8 days in fridge.

PVA has been used as a gelling agent for the fabrication of multimodal phantom complexes, which are similar to soft tissue, providing a unique tool for application in a variety of uses [26]. The disadvantage is due to its manufacturing process, which requires detailed and precise temperature control, using the freeze-thaw technique, in addition to a long post-manufacturing time [25-27].

Gelatin/Agar Agar

Gelatin and agar-agar simulators are useful for teaching and learning different US-guided techniques. Easy to build with kitchen products, it consists of a gelatin mold in which a tubular elastic structure is inserted (fig 1). Compared to gelatin, agar is much more durable and resistant to touch.

Various studies have shown the echogenic properties of gelatin, suitable for vascular access training, with low costs and easy preparation [28,29]. Its major advantage, apart from its price, is the fact that its transparency can be changed. However, they do not mimic muscular or tendinous structures; they leave the path of the needle mark and depending on the concentration of the gelatin used in the manufacture, they can be easily damaged (fig 2).

Several published articles describe the elaboration of these homemade simulators with different components and expose their strengths and weaknesses [28-34] (fig 2). To highlight a model that differs from others, the one made by Leenders, Bruijnen, and Elshof is made of a combination of pre-filled tubes and an affordable silicone layer that mimics the skin and, most importantly, it has a relative shelf life due to the addition of the antiseptic solution to the gelatin mixture. However, its educational efficacy for two-hand movements or eye-hand coordination has not been established [32]. There is another model where the gelatin is covered with a hydrocolloid dressing for the skin, which minimizes the physical alteration of the surface by the transducer or the needles and reduces biological degradation due to bacterial propagation [33].

Animal Model

Biological phantoms are manufactured manually using chicken, turkey or pork thighs as the muscular structures, and different elastic components as the vascular structures such as catheters, drains, or serum infusion systems (fig 3). A real simulation of both tissue imaging and cannulation is successfully achieved, being an ideal option for US-guided vascular access training [15].

Advantages include low cost, wide availability, easy transportation, realistic feel of tissues, presence of blood vessels, bones, and nerves, as well as the ability to embed targets in the model, allowing for different degrees of complexity depending on vessel diameter and depth.

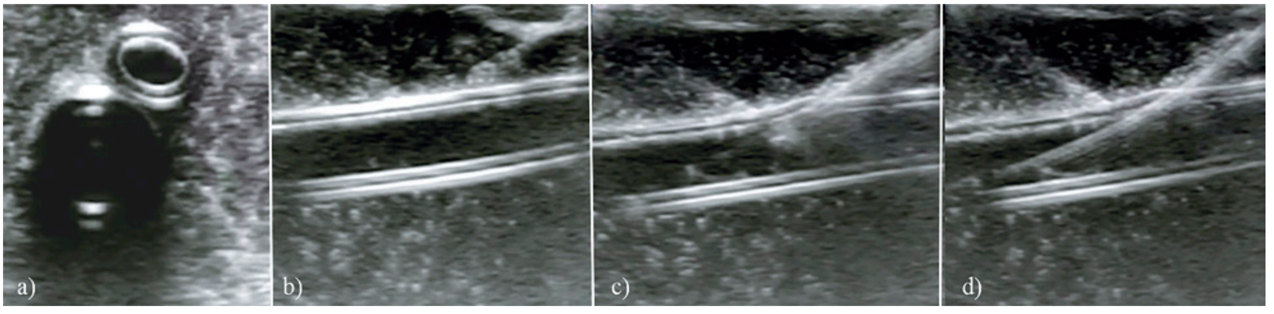

Fig 2. Gelatin homemade phantom: a) ultrasound transverse view; b) ultrasound longitudinal view; c) ultrasound guided needle insertion in longitudinal view; d) ultrasound guided guidewire progression in longitudinal view.

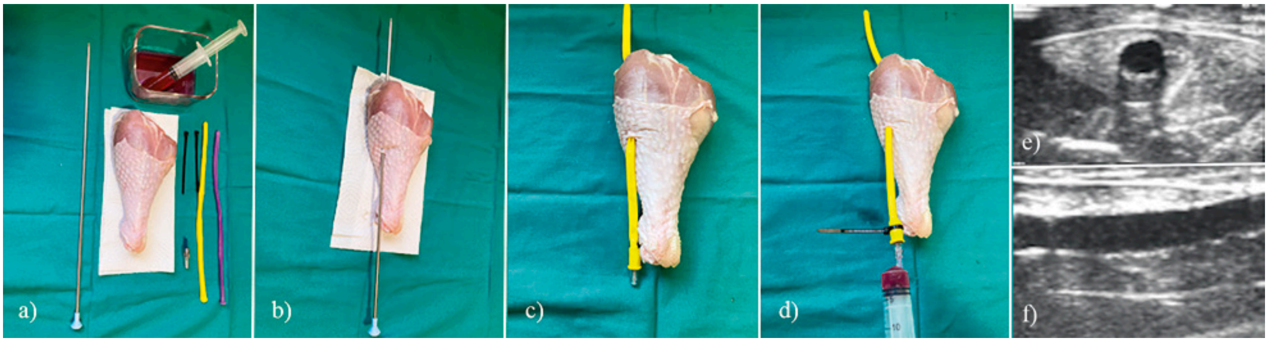

Fig 3. Turkey homemade phantom: a) material needed for phantom preparation; b) creating the space for the balloon; c) once the balloon is inside, a needle-free connector is connected and secured with a bridle; d) the balloon is filled with liquid; e) ultrasound transverse view; f) ultrasound longitudinal view.

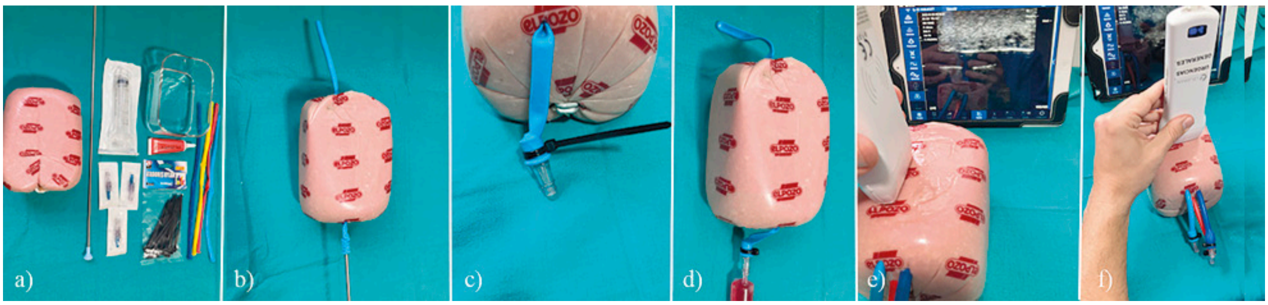

Fig 4. Ham homemade phantom: a) material needed for phantom preparation; b) inserting the balloon through the ham; c) balloons are filled with liquid; d) piece of ham with long balloons inside filled with liquid; e) ultrasound longitudinal scan; f) ultrasound transverse scan.

As for disadvantages, the need for refrigeration for preservation, with a half-life of one week, the relatively long preparation time, and the possibility of air trapping during the preparation of the models that reduces US imaging quality should be mentioned [35].

Using a piece of cooked York ham or bologna as phantoms is a low-cost homemade alternative with very accessible materials. In addition, the model allows for multiple cannulations while maintaining its functional integrity (fig 4). Its use for training improves eye-hand-probe coordination, increasing safety, but indeed it does not allow adaptation to the anatomical references of any venous access [36].

Tofu

The tofu model is simple, inexpensive, and portable (fig 5). It provides an opportunity to practice US-guided needle localization and advancement. Some target structures, i.e., wood and wire, can be inserted inside the phantom [37]. Its main application is to train in directing the needle to the target. However, it has great disadvantages, such as loss of US imaging quality and degradation of the model in less than 20 perforations. In addition, the model constitutes an excellent growth medium for bacteria, which facilitates the probe sonde contamination, increasing the risk of patient infections [35].

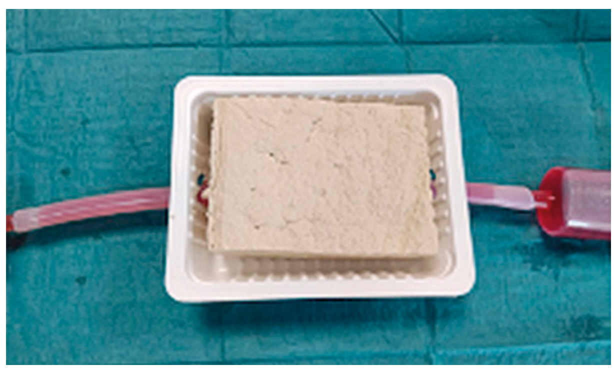

Fig 5. Tofu homemade phantom. Block of tofu with plastic tubes inside filled with liquid

3. Cadaver

Both fresh and lightly embalmed cadavers have been used as simulators to practice common US-guided procedures before patient care. Embalmed cadavers are primarily used for anatomy studies because the free flow of fluid in a cannulated post-mortem vessel leads to extravasation of fluid, which eliminates the usefulness of the cadaver for other procedures. Furthermore, fluid extravasation results in distortion of normal anatomy and deterioration of US image quality. Some studies attempted to reduce this limitation by infusing fluid directly into fresh cadaveric vessels, but local fluid extravasation and subsequent deterioration of US images continued to be observed after only a few cannulation attempts [38]. An additional disadvantage is that the repetitive use of punctures greatly damages the corpse, with a short lifetime. However, as an advantage, it should be mentioned that imaging cadaver tissues provide realistic information, similar to that of a living patient [39].

Conclusions

Commercial-grade US phantoms are expensive, and although they are reusable, their cost can be a barrier to simulation-based training. Homemade phantoms are a cost-effective, highly useful tool for teaching vascular access using US**.** For the elaboration of the homemade ones, different substances and elements are usually used to produce varied echogenicities and geometries. Specifically, animal-based ones provide more realistic tissue feedback and have a background echogenicity that is closer to that of human tissue. However, they suffer from a short shelf life even with the various methods described for preserving and preparing them. A powerful alternative is the use of PVA or modified mixtures of this material, which would be better suited to cannulation simulation with high functional fidelity.

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Conflict of interest: none

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