Research Article

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Evaluation of Optic Nerve Sheath Diameter Measurements in Eye Phantom Imaging using POCUS and AI

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ABSTRACT

The aim of this review is to provide a wide overview of optic nerve ultrasound normal values assessment using eye phantom imaging techniques using POCUS. We examine the suitability of commercially available, low-cost, portable ultrasound devices that can be combined with artificial intelligence algorithms to reduce the training required for and cost of in-field optic nerve sheath diameter measurement. Several disorders can affect the optic nerve and their differential diagnosis can be challenging, requiring expensive or uncomfortable tests. Elucidation of its underlying disease and follow up may require expensive or uncomfortable tests or even invasive procedures like lumbar puncture. Ultrasound has been widely used for this purpose, but it requires knowledge and skill to give reliable results.

***Methods:** Transorbital sonographic measurement of optic nerve sheath diameter (ONSD) was measured by point-of-care ultrasound machines on phantom ONS model. Measurements were analyzed for mean error and variance and tested for significance using regression analyses. We developed a low cost, easily made phantom model that may assist with training and improve the quality of sonographic measurements of the ONSD. This study aims to: (1) provide a step-by-step description of producing a sonographic phantom of the posterior chamber of the eye; and (2) validate the model as a realistic educational tool utilizing in vivo and phantom ONS images obtained by ultrasound.*

***Outcome:** Accurate ONSD measurement is possible utilizing POCUS. Measurement of the optic nerve sheath diameter (ONSD) via ultrasonography has been proposed as a non-invasive metric of intracranial pressure that may be employed during in-field patient triage. However, first responders are not typically trained to conduct sonographic exams and/or do not have access to an expensive ultrasound device. Therefore, for successful deployment of ONSD measurement in-field, we believe that first responders must have access to low-cost, portable ultrasound and be assisted by artificial intelligence (AI) systems that can automatically interpret the optic nerve sheath ultrasound scan.*

Keywords
Ultrasound computer tomographs, Ultrasound waves, X-ray, Sound pressure.

Introduction

Ultrasound computer tomographs (USCT) use ultrasound waves for creating images. In the first measurement step a defined ultrasound wave is typically generated with Piezoelectric ultrasound transducers, transmitted in direction of the measurement object and received with another or the same ultrasound transducers. While traversing and interacting with the object the ultrasound wave is altered by the object and transmits information about the object. After being recorded the information from the modulated waves can be extracted and used to create an image of the object after image acquisition. Unlike X-ray or other physical properties which typically provide only one type of information, ultrasound provides multiple modes of information about the object for imaging: the attenuation the wave's sound pressure experiences reflect the object's attenuation coefficient, the time-of-flight of the wave gives speed of sound information, and the wave scatter indicates the echogenicity of the object (e.g. refraction index, surface morphology, etc.). Unlike conventional ultrasound sonography, which uses phased array technology for beam formation, most USCT systems utilize unfocused spherical waves for imaging. Most USCT systems aim for 3D-imaging, either by synthesizing ("stacking") 2D images or by full 3D aperture setups. Another study goal is quantitative imaging instead of only qualitative imaging (Figure 1).

3D ultrasonography in the ambulatory and critical care settings has become an invaluable diagnostic tool for patients presenting with traumatic or atraumatic vision loss and ocular complaints. For properly trained ophthalmologists, sonographic bedside evaluation is intuitive, easy to perform, and can accurately diagnose a variety of pathologies. Also, they are fast in data acquisition as they do not require time-intensive mechanical manipulation of the probe. Detection of pathology includes detachment or hemorrhage of the retina, choroid or vitreous, lens dislocation, or subluxation, globe rupture or scalopetaria retinae, commotio retinae, retrobulbar hematoma, ocular and orbital foreign bodies, infections, cellulitis, inflammation, tumors, orbital compartment syndrome and increased optic nerve sheath diameter that can be assessed in the setting of suspected increased intracranial pressure and many more conditions. The ocular anatomy is easy to visualize with sonography, however, orbital ultrasound remains a challenge. Over the last two decades, a large number of scientific publications have documented that 3D ultrasound in emergent or critical care settings is an accurate diagnostic tool and expands and improves emergency diagnosis and management [2].

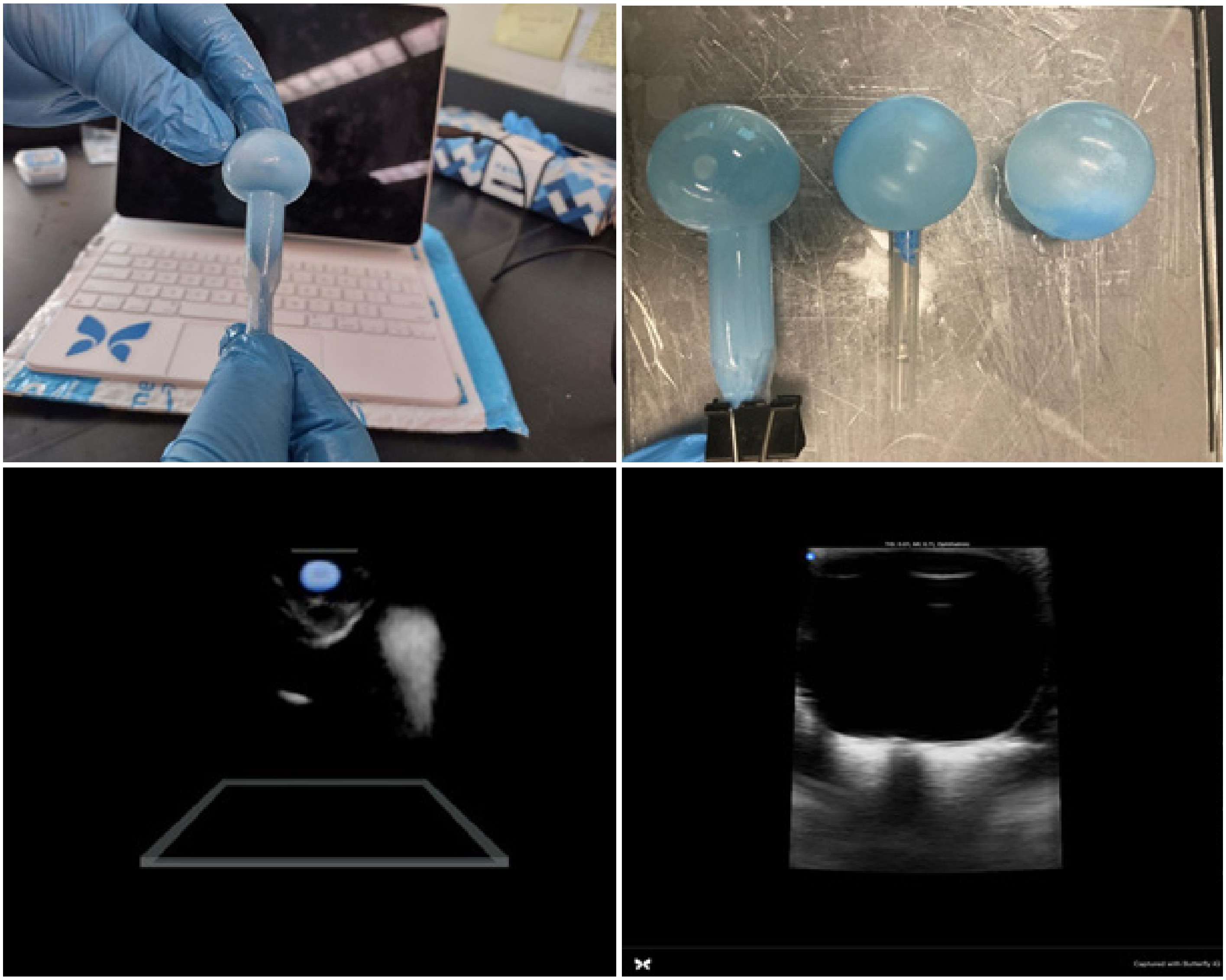
Ultrasonography of the optic nerve sheath (ONS) and measurement of its diameter (ONSD) is a non-invasive technique for detecting elevated intracranial pressure (ICP) (e.g., in traumatic brain injury (TBI) patients) [1-5]. The ONS is a continuation of the dura mater and distends according to cerebrospinal fluid pressure. The technique relies on two key points: (1) An optimal view of the ONS being identified in B-mode ultrasound, (2) an ONSD measurement made 3 mm from the papilla and perpendicular to the orientation of the optic nerve (ON). Ideally, ONSD values greater than a predetermined threshold are suggestive of elevated ICP. For safety, it is important that the ultrasound settings used during ONSD measurement meet the stringent Food and Drug Administration (FDA) limits on acoustic output for ophthalmic ultrasound [1].

Material and Methods

Validation of a Low-cost Optic Nerve Sheath Ultrasound Phantom.

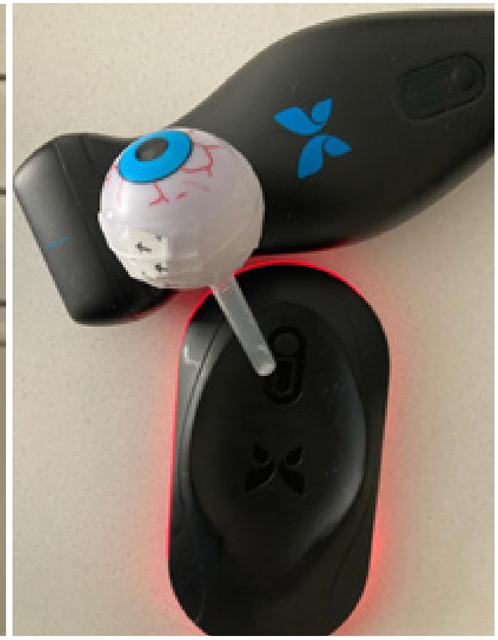
TISSUE-MIMICKING PHANTOM

Phantoms are objects designed to mimic the properties of human tissue and are used to study and develop new medical imaging and treatment options. The development of phantoms that accurately and reliably mimic the properties of human tissue is extremely important in the field of MRgFUS. Phantoms are used in quality assurance and validation of new imaging and treatment techniques. A variety of commercial phantoms for use with ultrasound or MR are available, however we believe that fabricating phantoms with custom shapes and tissue properties is essential to our research process. We have developed a methodology for fabricating gelatin phantoms that successfully mimic many of the acoustic, thermal and mechanical properties of human tissue. These phantoms are relatively simple to make and easily modifiable which allows them to be used for a variety of experiments.



Four ingredients are used to create the novel modified PVC ultrasound phantom mixture: M-F Manufacturing (Fort Worth, TX) regular liquid plastic PVC polymer and diethyl hexyl adipate plasticizer softener, mineral oil, and chalk powder. Different ratios of PVC to softener to mineral oil are used to create phantoms with varying echogenicity and needle force characteristics. Mixture 1 used a volume ratio of 9:1:2 of PVC polymer to softener to mineral oil. Mixture 2 used a ratio of 11:0:1. Mixture 3 used a ratio of 3:0:1. All 3 mixtures added 1 g of chalk powder for every 150 mL of total mixture volume. Doping agents, such as chalk powder, are used to increase the echogenicity of a material and can be added to many phantom materials. The PVC, softener, and mineral oil are mixed thoroughly under a fume hood in a pot and slowly heated to approximately 175°C, stirring frequently to ensure even heating and homogenous mixing. When the material begins to thicken and turn from a milky white color to translucent, chalk powder is slowly added while stirring, taking care to minimize clumping of the powder. Once the material has turned translucent, it is removed from heat and poured into the desired phantom mold. Any required internal structures (such as silicone tubing to act as vessels) should be positioned in the phantom material before the material solidifies. The mold is then left to cool to room temperature. If multiple layers of modified PVC are desired, it is best to wait to pour the additional layer until after the previous layer has hardened, but while it is still warm. This improves adhesion between layers and prevents them from mixing. Finally, extract the solidified and cooled material to complete the phantom (see Table, Supplemental Digital Content 1, for a summary of these instructions).

The manufacturer of the PVC polymer recommends that ventilation, such as a vent or fume hood, is used during heating the material to minimize inhalation of vapor, which may cause minor irritation to eyes or skin when exposed to excessive amounts. A respirator is recommended for use in areas with restricted ventilation. It is also important to not heat the PVC polymer over 235°C, which can cause the material to burn and decompose releasing toxic fumes.

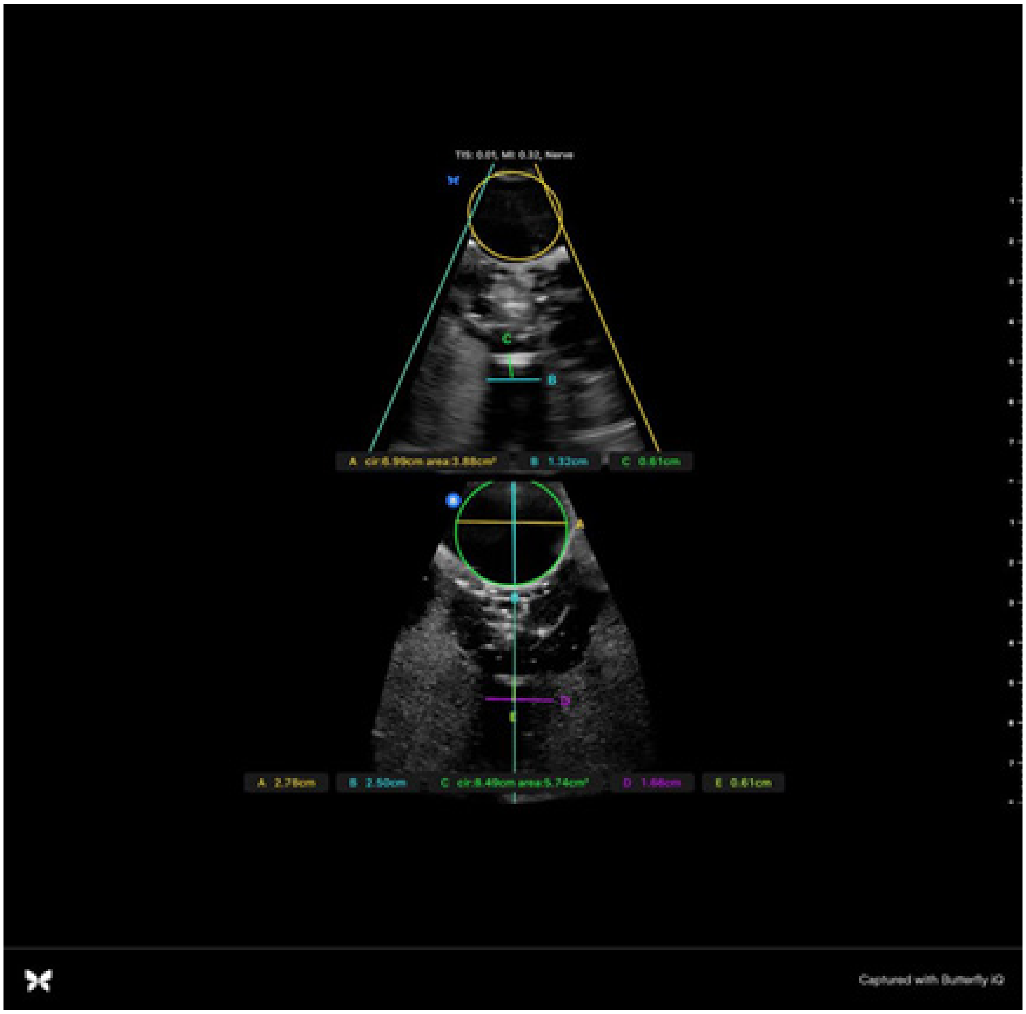


The ONS phantom is constructed utilizing the following: a 40-mm diameter ping-pong ball, assorted sizing of clear vinyl tubing, superglue or waterproof sealant, a drill with assorted bits, unflavored gelatin, sugar-free psyllium powder (e.g., Metamucil Sugar Free Dietary Fiber Supplement, Procter & Gamble, Cincinnati, USA), 18 gauge needle, 30 mL syringe, 473.176 mL plastic cups (e.g., Solo Plastic Party Cup, Dart Container Corporation, Mason, USA), and water (Figure 1A). To make the ONS portion of the model, a hole was drilled in the bottom of the disposable cup that matched the outer diameter of the clear vinyl tubing approximating the desired ONSD (for sizing, note that the outer diameter tends to correspond with sonographic ONSD). A section of tubing 7 cm long was cut. All but 2 mm of the tubing was inserted through the bottom of the cup and stabilized in a vertically plumb orientation in the middle of cup using a stylet (e.g., drill bit fixed with tape to brim of cup; Figure 2A). The tubing protruding from the bottom of the cup should be tight-fitting to ensure a tight seal, and its shallow profile allowed the cup to sit flush on the countertop (Figure 2B). This ONS portion was set aside.

The gelatinous matrix used to suspend our phantom eye and ONS was formed using a procedure described by Kendall and Faragher [5] by combining water, unflavored gelatin, and sugar-free Metamucil. Briefly, 250 mL water was boiled, then three packets of gelatin were gradually whisked over a medium heat until the gelatin was completely dissolved. Next, one tablespoon of Metamucil was added and whisked until it completely dissolved. With a spoon, the remaining bubbles were skimmed off. If clumps were present, a sieve was used to remove them. Lastly, this mixture was poured into the plastic cup with the ONS portion of the model. The cup was filled flush to the level of the upper vinyl tubing and placed in the refrigerator for 1–2 hours or until firm. Once the gelatin congealed, the stylet was removed. To make the eye portion of the model, two small puncture holes 2 mm apart were made on the ping-pong ball with a straight needle and syringe. One hole was used to fill the ball with water until all the remaining air was displaced through the other hole. A small amount of waterproof sealant (e.g., Gorilla Super Glue, Gorilla Glue Company, Cincinnatti, USA; Loctite Stik'n Seal outdoor adhesive, Henkel, Rocky Hill, USA, etc.) was applied over the holes and allowed to cure.

To connect the ONS and eye portions of the model, a small portion of super glue adhesive was applied to the exposed cross section of tubing in the cup with the ONS and congealed gelatin. The cup was placed in the refrigerator and the ping-pong ball was carefully positioned atop the vinyl tubing (Figure 2C). This can be challenging when smaller diameter vinyl tubing is used, therefore, a clean, perfectly horizontal cut of tubing is key. A second batch of the gelatin–Metamucil mixture was made. The second layer of gelatin was gently poured on top of the previously congealed layer until the gelatin completely submerged the ping-pong ball. Care was taken to ensure that the ping-pong ball did not fall off the tubing. The phantom was left in the refrigerator until firm, at which point it was ready for use (Figure 1B). For optimal imaging of this ONSD, low gain settings will minimize reverberation artifact produced from the circular walls of the ping-pong ball. Construction of this model required ~30 minutes, with an additional 30 minutes needed for congealing time. The cost of each model was <$5 USD. Ultrasound phantom models should be refrigerated when not in use to promote longevity [6-15].

Phantoms must have acceptable tissue-mimicking properties. As used in this study, gelatinous matrix made from low-cost, readily available products provide realistic simulation of periorbital soft tissues. The plastic ping-pong ball is hyperechoic, and exaggerates the fluid-tissue interface of the eye. Water infused into the ping-pong ball approximates the hypoechoic humors of the eye, whereas (hollow) vinyl tubing produces a crisp sonographic signal to adjacent gelatinous matrix similar to that of *in vivo* ONS (Figure 4).



Together, these features make our model a close approximation of posterior ocular anatomy, and provide the substrate to teach the ONS technique. Additionally, although not presented here the authors have successfully introduced objects into the phantom (e.g., monofilaments) that mimic orbital foreign bodies and retinal/vitreous detachments. Further refinements to this model could easily be made to broaden its utility (e.g., engineer anterior anatomy, etc.). Simulating ocular anatomy is fundamental to the utility of phantoms designed to teach ONSD measurement. Other phantoms have been developed to simulate ocular pathology, including dilatation of the ONS' [16].

Discussion

Pathological conditions affecting the optic nerve can result in optic nerve neuropathy, a term describing a range of disorders, including optic neuritis, glaucomatous optic neuropathy, ischemic optic neuropathy, and compressive neuropathies through trauma or idiopathically. These conditions often lead to vision impairment or blindness, making their early detection and accurate diagnosis a crucial need in the field of ophthalmology [17,18]. Conventional diagnostic methods for optic nerve neuropathy include clinical evaluation, visual field testing, and imaging techniques such as optical coherence tomography (OCT) and magnetic resonance imaging (MRI) [19]. While these methods provide valuable insights, they have limitations that include a lack of real-time assessment, high costs, and limited portability. It is also much more time-consuming, which prolongs the course of diagnoses and management. As a result, there has been growing interest in developing alternative diagnostic approaches, with ultrasound imaging emerging as a promising candidate. Ultrasound imaging, widely employed in various medical fields, offers several advantages for evaluating optic nerve neuropathy. It provides real-time, dynamic imaging of tissues, is non-invasive, cost-effective, and can be conducted at the bedside [20]. These features make ultrasound an attractive option for detecting optic nerve abnormalities. Phantom tissue models, designed to mimic the acoustic properties of human ocular tissues, are invaluable for preliminary investigations and method development. They provide a controlled and reproducible environment for refining ultrasound techniques and assessing their diagnostic potential [21]. Real tissue, on the other hand, represents the complexity of human anatomy and physiology, acting as a crucial bridge between controlled experimental settings and clinical application.

This scientific paper aims to evaluate the efficacy of ultrasound in detecting optic nerve neuropathy, comparing them in two distinct models: phantom and real tissue. Our investigation employs POCUS ultrasound, meticulously designed phantom tissue models, and real tissue samples obtained from patients with confirmed optic nerve neuropathy. The primary objectives of this study are image quality, diagnostic accuracy, feasibility and safety. We will assess the clarity, resolution, and contrast of ultrasound images to determine the extent to which optic nerve abnormalities can be visualized in both phantom and real tissue models. Sensitivity and specificity of ultrasound in detecting optic nerve neuropathy will be evaluated, comparing its performance in phantom and real tissue models. A critical examination of the safety profile of ultrasound will be performed, considering any potential risks and patient comfort. By addressing these key aspects, we hope to evaluate the strengths and limitations of ultrasound in diagnosing optic nerve neuropathy in both phantom and real tissue settings. Furthermore, our findings may lay the groundwork for the development of more advanced ultrasound techniques, potentially enhancing the early detection and management of optic nerve neuropathy. The ultimate goal of this research is to contribute to the growing body of knowledge regarding the application of ultrasound in ophthalmology, with a potential positive impact on patient care.

In this paper, we will present a comprehensive analysis of our findings, discussing their implications for the field of ophthalmology and the potential for integrating ultrasound into the routine diagnostic and management protocols for optic nerve neuropathy. We believe that our research represents a critical step towards advancing the diagnostic tools available to ophthalmologists, ultimately benefiting the patients who rely on timely and accurate diagnosis and treatment.

Conclusions

Simulation for ultrasound training is a useful tool in EM physician education [3]. Although performing ocular ultrasound on patient models is relatively safe, phantom models are convenient, easily accessible, and allow for prolonged scan time without endangering injury to the retina of patient models.

Unfortunately, application of the ONSD technique has been mired in inconsistencies in the measurement protocols (resulting in differences in the predictive power) and thresholds across studies [2,4-10]. Many hypotheses have been suggested for these inconsistencies, including: whether left/right eye measurements are averaged, which orientation (sagittal or transverse) the measurement is made, patient demographics, and whether the ONS itself is being measured. The latter has been the focus of recent scrutiny, as color doppler has shown that acoustic shadow artifacts can create ONS mimics that do not correspond to known anatomy [1,11]. This has led to the recent proposal of a standard measurement technique via the CLOSED protocol in which the ONS is distinguished from acoustic artifact by color doppler of optic vasculature landmarks [1,12]. However, as with many of the previous measurement proposals, multi-center clinical trials that assess inter- and intra-operator variability are still needed.

In addition to the standardization of technique, automated ONSD measurement approaches have been proposed to remove the subjectivity and human error in determining the boundaries of the ONS [13-15]. In particular, Moore et al. developed an automated algorithm that could correctly identify and measure ONSD from blind (no B-mode shown to the probe operator) scans of an ocular phantom [14]. This type of AI-aided system, paired with inexpensive, portable, point-of-care ultrasound (POCUS) devices, could allow for diagnosis of elevated ICP at the point-of-injury by reducing the training burden of far forward operators. Such a capability could have an important impact on combat casualty care, mass casualty triage, and triage in low resource environments for traumatic brain injuries.

Declaration of Helsinki

This review is adhered to the ethical principles outlined in the Declaration of Helsinki as amended in 2013. (https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/).

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