

Augmented Reality Ultrasound Guidance for Central Line Procedures: Preliminary Results

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Abstract. Central line procedures are interventions in which a needle is placed in the jugular vein in the patient's neck inferior to the carotid bifurcation. In these procedures, avoiding the puncture of the carotid artery is of upmost importance as it can cause severe neurological consequences or death. Often, these procedures are performed under ultrasound guidance, meaning that a linear ultrasound probe is held to the patient's neck in which the interventionalist can visualize both the carotid artery and jugular vein. However, due to the geometry of the interventional scene, the needle must be placed out-of-plane with the ultrasound and the needle cannot be fully visualized, only a cross-section thereof. This lack of visualization can lead to issues gaging the correct penetration depth. This paper presents preliminary results on an augmented reality (AR) needle guidance system in which a tracked needle and ultrasound fan are simultaneously visualized in their entirety. This AR guidance system is compared against traditional ultrasound-only guidance on a neck phantom. The use of the AR system significantly reduces the intervention time (average decrease of 3.51 ± 1.44 s) and normalized path length (average decrease of 150 ± 40 %) implying that the use of such as system makes the procedure easier for the interventionalist ($n = 36$, $p \leq 0.05$). This AR system has gained regulatory approval and is scheduled for clinical trials in humans.

Keywords: Central line procedure · Needle guidance · Ultrasound-guided interventions · Augmented reality

1 Introduction

Central venous cannulation, predominantly in the internal jugular, femoral, and subclavian veins, is a widely performed procedure in current medical practice often used in intensive care units and operating rooms. Among the main central venous catheter sites, the right internal jugular vein (IJV) cannulation is perhaps the most popular method providing access to the deep venous system

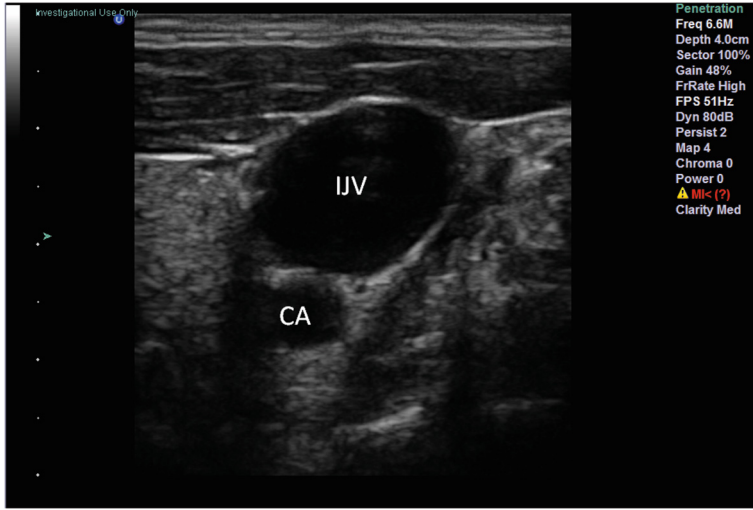


Fig. 1. Ultrasound images of a healthy volunteer. The image has been labeled with the carotid artery (CA) and internal jugular vein (IJV) for reference.

for a large number of applications including hemodynamic monitoring with pulmonary artery catheter, access for prolonged intravenous therapy, and access for endomyocardial biopsy [4]. Over 5 million central venous catheters are inserted annually in the US alone with an overall complication rate of 15 % [7]. Inadvertent carotid artery (CA) puncture can occur either by needle placement directly into the artery lumen, or after the cannulating needle transverses the IJV [8]. Severe neurological problems and life threatening complications may arise during central venous needling and catheterization due to arterial puncture and hematoma [5, 7, 9]. A safe needle and catheter placement is of utmost importance in central venous catheterization procedures.

Commonly, the IJV is identified using an external anatomical landmark-guided technique and then the introducer needle and subsequently the catheter are inserted blindly. However, an aberrant anatomical position of the IJV (in 8.5 % of patients) would make this technique unreliable even in the hands of the experienced interventionalists [4]. The reported failure rate to access to the IJV ranges from 7 %–19.4 % depending, in part, on the operator's experience [4].

Ultrasound (US) has been used off-line to localize the CA, the IJV, and the insertion site prior to cannulation. An ultrasound image of a healthy volunteer is shown in Fig. 1. The pulsation of the CA is visible under real-time US and has been suggested to be used to distinguish it from the IJV [8]. Real-time US has also been employed to guide needle placement inside the IJV. Ultrasound guidance during internal jugular catheterization has been shown to reduce the insertion time, the rates of unsuccessful catheterization, CA puncture, and hematoma formation [7].

The IJV is at a depth of 1.0–1.5 cm beneath the skin surface in most patients [2] and can be easily visualized in US using a 5–10 MHz linear transducer [7]. However, complications in central venous cannulation still arise in spite of real-time US guidance [3]. Blaivas *et al.* [3] reported that 68% of emergency medicine residents, undergone 2-day US-guided vascular access training, inadvertently penetrated the posterior wall of the IJV during US-guided cannulation in a phantom study. The main reason for the failure of the US guidance in preventing any complication in IJV cannulation is that the US guidance is provided using a transverse approach, where the US image plane is perpendicular to the length of the vein [3]. As a result, only the cross section of the venous lumen is seen in the US image. In addition, the needle is inserted out-of-plane with the ultrasound and as a result only its cross section appears in the US image, as a bright spot, making it difficult to distinguish the needle tip from needle shaft. Therefore, even under US guidance, issues arise regarding the correct needle placement and evaluation of the penetration depth.

The purpose of this work is to present a novel guidance system, which has been approved for clinical evaluation for the IJV cannulation procedure to facilitate needle navigation and placement in the IJV and improve the overall safety of this procedure. The proposed guidance system consists of an augmented reality (AR) environment, in which a tracked needle, its trajectory, and real-time US images are simultaneously visualized in the same coordinate system. The AR guidance system is compared against traditional US-only guidance on a neck phantom in a user study. This system has the potential to improve accuracy and safety of the central venous cannulation procedure in a clinical setting and has received regulatory approval for clinical trials in humans.

2 Methods

2.1 Augmented Reality Guidance System

An AR guidance platform was developed, which allowed for the US image and a virtual representation of the needle to be displayed simultaneously in the same coordinate frame. Ultrasound images were acquired using a SonixTouch US scanner and a magnetically tracked L14-5/38 ultrasound probe (Ultrasonix, Analogic Corporation, MA, USA). An Aurora magnetic tracking system (NDI, Waterloo, ON, Canada) was used to determine the physical location and orientation of the ultrasound probe and needle for use in the visualization. The US probe was calibrated using a line fiducial as described in [1]. The needle used was an 18G Aurora needle, which has a 5DOF magnetic sensor integrated into its stylet's tip. To improve the usability of the AR system, the virtual needle was equipped with a representation of its trajectory as well as a sequence of uniformly spaced 1 cm markings along the needle and its trajectory, giving the user a rapid understanding of the depth of penetration beyond, or remaining depth to, the ultrasound plane. The open source Atamai Image Guided Surgery (AIGS) library¹ was used

¹ <https://github.com/awiles/AIGS>.

for communication with tracking systems. The Visualization Toolkit (VTK)² and QT were used for visualization and user interface³, respectively. The AR system visualization is shown in Fig. 2.

The developed needle guidance system is similar to the commercial SonixGPS (Ultrasonix, Analogic Corporation, MA, USA) system. However, it uses an Aurora tracking system instead of Ascension, which is used in SonixGPS. In addition, our custom AR system for needle visualization is substantially different from that used in SonixGPS and provides a 3D visualization environment. The advantage of our visualization system is that the needle can be guided and visualized in any orientation relative to the US probe (in-plane and out-of-plane), and the user can adjust the vantage point of the virtual camera to any arbitrary angle as needed. As SonixGPS is not widely available across all institutions/hospital, and the blind/US-guided technique is the current gold-standard, we conduct our study to illustrate the efficacy of the developed AR system compared to the clinical gold-standard.

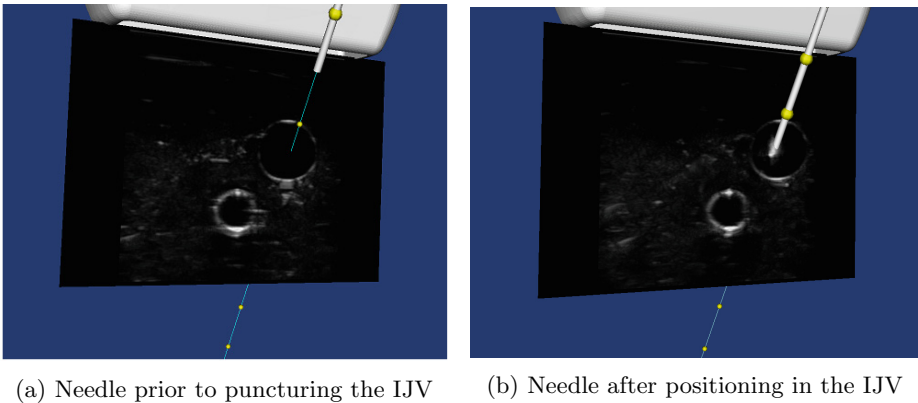


Fig. 2. Augmented reality needle guidance platform.

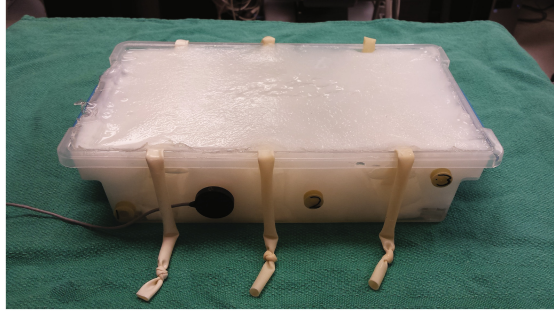
2.2 Phantom Construction

A phantom was designed to represent three IJV and CA sets for a user study, as shown in Fig. 3a. The IJV and the CA were simulated as hollow tubes inside a tissue mimicking polyvinyl alcohol (PVA-C) block (10 % PVA-C). In order to create the hollow tubes, plastic straws and metal tubes of different sizes were used.

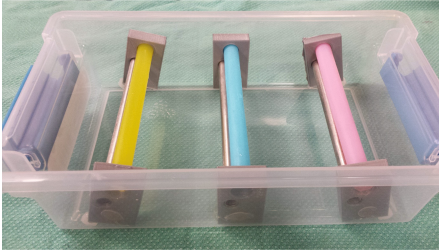
The mean diameters in adults of the right IJV and the common CA is 14 ± 5 mm and 6.5 ± 1.0 mm, respectively [6,10]. The IJV is usually positioned in laterally and anteriorly to the CA at a depth of 1 to 1.5 cm below the skin [4].

² <http://www.vtk.org/>.

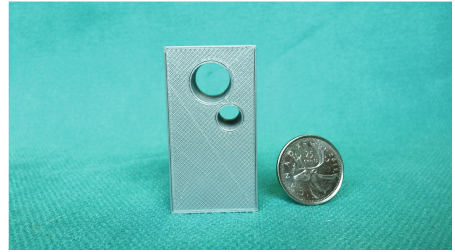
³ <http://www.qt.io/>.



(a) User Study Phantom consisting of a PVA-C block with water-filled tubes simulating the CA and IJV



(b) Phantom prior to introduction of PVA-C, showing three CA/IJV vascular combinations



(c) Rapid prototyped support block to keep the straws and tubes in place

Fig. 3. Phantom employed in user study.

In our phantom, the diameter of the hollow tubes representing the IJV and the CA were 12.3 mm and 8 mm, respectively. Three supporting blocks, Fig. 3c, were placed at three different angles along the length of the container on each side in order to account for anatomical variations and reduce training effects. Straws and metal tubes were placed inside the holes of the support block as shown in Fig. 3b. The plastic container was then filled with PVA-C and subjected to two freezing-thaw cycles, after which the straws were removed. A penrose tube filled with water was passed through the smaller tube so that it could be pulsed, by squeezing one end periodically, in order to create a more realistic representation of the CA as visualized in US. An Aurora 6DOF magnetic sensor, 25 mm Disc, (NDI, Waterloo, ON, Canada) was placed on the phantom box as a tracking reference to accommodate for any overall shift. An ultrasound image of the phantom is shown in Fig. 4.

2.3 User Study

Eighteen novice participants were recruited. After a brief training phase (approximately 20 min) in which the participants could familiarize themselves with both the US and AR guidance systems, the participants performed a set of two central

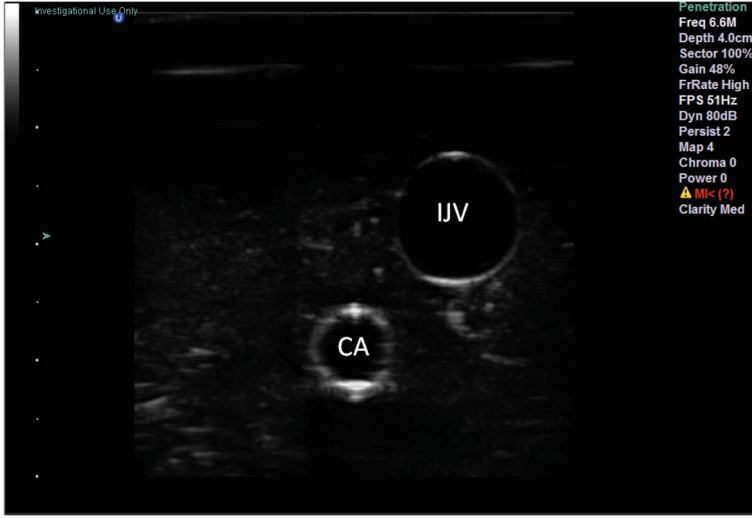


Fig. 4. Ultrasound images of the phantom. In comparison to Fig. 1, the phantom provides a realistic US image of the IJV and CA.

line procedures, one with AR guidance and one with US only. The order in which these were performed was randomized to control for the training effect. The task was defined as complete when the participant reported the needle to be in the IJV in the phantom. After a period of one week, each participant performed an additional set of central line procedures and the opposite order was used. In this study, the desired target for needle placement is any location within the phantom IJV. This is similar to the clinical central venous cannulation procedure in which any location along the IJV inferior to the carotid bifurcation is considered adequate for central line insertion.

For each procedure, two performance metrics were collected: procedure time and needle path tortuosity. The time taken to deliver the procedure was measured directly by our tracking software. Lower procedure times are desirable to minimize patient discomfort and to improve clinical workflow. The tortuosity of the needle path, how much the needle path deviates from a straight line during the procedure, is calculated using the normalized path length. The normalized path length is the ratio of the actual travelled path, divided by the length of a straight line connecting the start and end locations. Both lengths were collected directly by our tracking software.

3 Results

The results were processed using two-way ANOVA with the guidance system type (AR vs. US-only) and the trial number (1 to 4) as factors. To correct for multiple comparisons, the Holm-Bonferroni correction was used with a combined

significance of $p \leq 0.05$. The results displayed in Fig. 5 demonstrate that both the system type and trial number have a significant effect on both metrics with no significant interaction effect.

Box-plots organizing the data by the guidance system type are shown in Fig. 5. The 95 % confidence interval on the average improvement in terms of time for AR compared to US-only guidance is 3.51 ± 1.44 s. The 95 % confidence interval on the average improvement in terms of needle path tortuosity for AR compared to US-only guidance is 150 ± 40 %. Thus, AR guidance shows a significant improvement in terms of procedure time and needle path tortuosity. In addition, AR showed a lower interquartile range than US-only guidance for both metrics, implying that performance in AR was more consistent across participants.

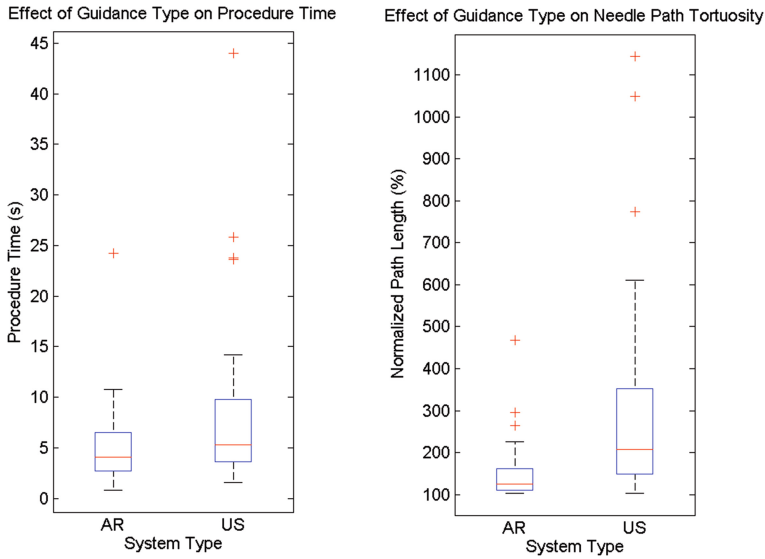


Fig. 5. Results organized by guidance system type. AR significantly outperforms US in terms of both time and tortuosity.

A significant training effect was detected in our analysis of variance. To examine this effect, the time and tortuosity results re-organized by trial are plotted in Fig. 6. Because there was no significant interaction between system type and trial number, Fig. 6 shows the results for ultrasound-only and AR guidance combined. For both metrics, there is a clear improvement over the first three trials which qualitatively confirms the existence of a strong training effect for novice users for the procedure as a whole. For both time and tortuosity, the interquartile range decreased over the first three trials while keeping a consistent lower bound indicating that not only was performance better on average, it is also more consistent amongst participants.

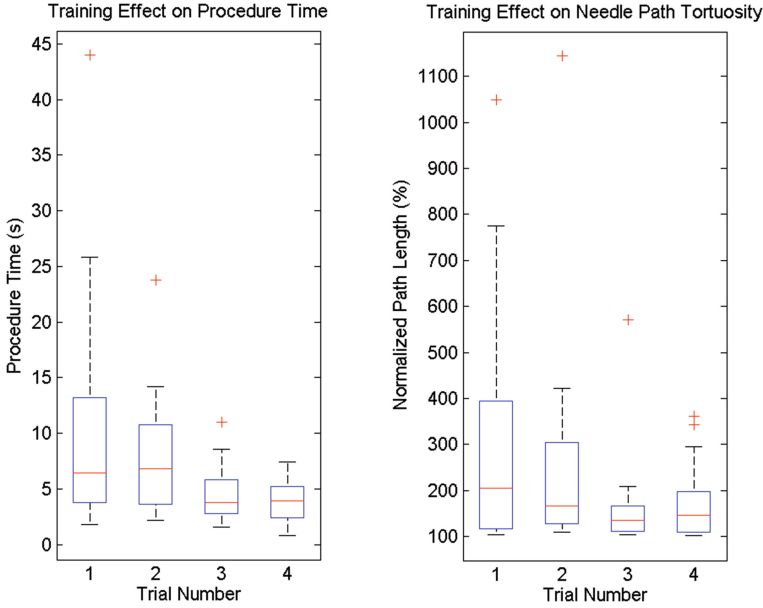


Fig. 6. Results organized by trial number. A significant training effect was observed for both metrics which is evident from the first three trials.

In terms of safety, there was only one incident in which the phantom CA was punctured, and this trial occurred under US-only guidance. A larger study is required to determine if there is a significance difference in terms of the number of carotid punctures given their infrequency under both guidance modalities.

4 Discussion

This study is a precursor to evaluating this system using medical practitioners and nursing staff who routinely perform central line cannulations. In this preliminary study, to establish the validation of the methodology, we investigated the performance of novice users guiding needle in a simulated central line procedure using an in-house designed phantom. The results indicate that AR guidance significantly outperforms traditional US-only guidance in terms of both time and needle path tortuosity, implying that the AR can make the central line procedure easier while minimizing patient discomfort. Additionally, AR showed more consistent performance than US-only guidance with fewer outliers and a tighter inter-quartile range, suggesting that the AR system can accommodate for variations amongst interventionalists, such as in the interpretation of the US images. Although these results are preliminary and use a novice participant group, they are promising as the AR guidance system enters clinical trials with expert interventionalists.

In addition to its use in an interventional setting, the proposed AR system could also be used for teaching purposes. As shown by Blaivas *et al.* [3], adequate training in central line procedures is a major concern deserving of greater attention. In this context, the AR system would teach the trainees how to interpret the ultrasound image with respect to the underlying anatomy and needle position so that they would be better able to perform the procedure using conventional US guidance. Such AR reality training has been shown to be beneficial for US-guided facet joint injections where it improved the safety and success rate compared with traditional US-only training [11]. While the main focus of our study was on the use of AR for guiding interventions, we did observe substantial training effects with the novice users. Our future work will better characterize these effects in central line procedures both with AR and US-only guidance and to repeat this experiment with expert interventionalists to better gauge clinical applicability.

5 Conclusion

In this paper, we propose and perform preliminary validation on an augmented reality (AR) guidance system tailored for the central line procedure. This AR system combined a magnetically tracked needle and ultrasound probe into a lightweight framework that is run directly from the ultrasound scanner itself. This system has been shown to significantly reduce procedure time and path tortuosity, improving the safety of the procedure. This system has received regulatory approval and is scheduled for clinical trials.

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