Acoustic lens improves superficial in-plane ultrasound-guided procedures – The significance of the beam width artefact

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ABSTRACT

Study objective: The three-dimensional shape of the ultrasound beam produces a thicker scan plane than most users assume. Viewed longitudinally, a needle placed lateral to a vessel just outside the central scanning plane can be displayed incorrectly in the ultrasound image as if placed intravascularly. This phenomenon is called the beam width artefact, also known as the elevation or slice thickness artefact. The goal of this study was to demonstrate the potential negative effect of the beam width artefact on the performance of in-plane ultrasound-guided vascular access procedures, and to provide a solution.

Design: Randomized, double-blinded study

Setting: Department of anaesthesiology and intensive care of a teaching hospital

Participants: 31 experienced (anesthesiologists and intensivists) and 36 inexperienced (anesthetic nurses) ultrasound users

Interventions: We developed an acoustic lens that narrows the scan plane to reduce the beam width artefact. The lens was tested in a simulated vascular access study.

Measurements: The primary endpoint was first pass success. Secondary endpoints were the number of punctures and needle withdrawals, procedure time, needle visibility and operator satisfaction.

Main results: First pass success was highly enhanced using the acoustic lens, with a success rate of 92.5% versus 68.7% without the lens (difference 23.8, 95% confidence interval 11.0–35.3, \( p < 0.001 \)). The total number of punctures needed to obtain intravenous access was also reduced using the lens (1.10 versus 1.38, difference 0.27, 95% CI 0.11–0.43, \( p = 0.002 \)). Procedure time, needle withdrawals, needle visibility and satisfaction were similar. Both inexperienced and experienced users benefited from the acoustic lens.

Conclusions: The beam width artefact has a significant effect on the performance of ultrasound-guided needle-based procedures. The efficacy of in-plane superficial vascular access procedures can be enhanced by narrowing the imaging plane using an acoustic lens.

1. Introduction

In superficial ultrasound (US)-guided vascular access procedures, successful cannula placement using the long axis (in plane) approach can be challenging despite ultrasound guidance. A common and frustrating experience during these procedures is an intra-arterial or peripheral vein needle or catheter that is perfectly placed according to ultrasound while it is still not possible to draw blood or advance the catheter into the vessel. Rotating the ultrasound transducer 90 degrees in the short axis will most likely reveal that the needle tip is placed just outside the vessel. (Fig. 1) In this paper, we will explain and provide a solution for this shortcoming of in-plane procedures.

The phenomenon described is caused by the behaviour of ultrasound in tissue and its representation on the US image, and is caused by the beam width, elevation thickness or slice thickness artefact [1,2]. This artefact has long been known, but its influence on the success of needle
structures are located in the same plane. This optical illusion is created by overlapping with structures from the central plane and suggesting that both the US plane and axial resolution are known to most US users, many are not familiar with elevational resolution, which is the resolution of the thickness of the US plane. Even experienced US users assume that the US beam is very thin, while in fact the beam has a three-dimensional shape with a finite, limited, yet noticeable width, the so-called beam width [3]. The thickness of the slice is relatively wide just after leaving the probe, then it narrows to its lowest level at the focus point and widens again with increasing depth. (Fig. 2).

This widened scan plane can produce images that may mislead US operators in long axis procedures. Acoustic signals from strong reflectors (needles) placed on the lateral side of the elevational plane will be picked up by the transducer and displayed on the 2D US image, overlapping with structures from the central plane and suggesting that both structures are located in the same plane. This optical illusion is created as the US machine reduces the three-dimensional US beam to a 2D image and thus compresses all structures within the elevation plane to a single plane. Consequently, intravascular needle placement is suggested when in reality the needle is placed beside the vessel. (Fig. 3a).

Since the beam width is smallest at the focus point of the US beam, reducing the beam width will also reduce this phenomenon: the needle is now placed outside the thinner US elevation-plane (Fig. 3b) and it will not be shown in the compressed 2D US image. Therefore, no optical illusions will be generated. It is also worth noting that the beam width reduction is achieved by decreasing the focus length, i.e. the focus becomes more superficial.

For in-plane vascular access procedures, the beam width artefact has clinical significance. Since peripheral veins, arteries or biopsy targets have diameters of approximately 2 mm, the beam width artefact can seriously decrease the success rate of US guided procedures. Indeed, failure rates up to 30% have been reported despite presumed visualization of adequate needle tip positioning [4–6].

The goal of this study was to demonstrate the potential negative effect of the beam width artefact and to develop a solution to minimize its effects on US guided in-plane procedures. First, the acoustic output of a commonly used probe for superficial vascular access was measured. Based on this output, an acoustic lens was designed which narrows the beam width and places the focus at the depth of the artery. Finally, in a simulation study, the performance of US guided vascular access with and without the acoustic lens was compared.

2. Materials and methods

2.1. Acoustic output

The acoustic output of the ultrasound transducer was measured with a hydrophone (Precision Acoustics, Dorchester, UK). This acoustic recording device with a frequency range of 250 kHz to 50 MHz is placed on a mechanically steerable platform in a temperature-controlled water bath at 37 °C. With computerized, miniscule steps, the hydrophone measures the acoustic pressure waves that are generated by the transducer and transmitted through the water [7]. By measuring the pressure waves at different locations in 3D space, the output of a probe can be characterized three-dimensionally and presented visually.

In the present study, the output of an L15-7iO vascular hockey stick probe (Philips, Bothell, WA, USA) was characterized using a Philips Epic 7G ultrasound system (Philips, Bothell, WA, USA) [8] The beam width of the probe is displayed in Fig. 4a. The beam has a thickness of approximately 1 mm at the focus point (asterisk) but becomes wider at decreasing depth, with a width of just over 2 mm at 5 mm depth and increasing to approximately 3 mm at less than 1,5 mm depth.

For comparison, the vascular probe is depicted next to the acoustic output of a common linear L12–4 probe (Philips, Bothell, WA, USA), which is also frequently used for vascular access (Fig. 4b). The beam width approaches 4 mm, i.e. almost double the size of the artery or vein. Thus, the beam width artefact is clearly more significant with lower resolution probes.

2.2. Lens construction

The beam width artefact will be minimal at the focus depth, as the beam width is smallest and the elevational resolution is highest at that depth. We hypothesized that a more accurate visualization of vessels and needles might be achieved with a lens with a more superficial focus. Therefore, acoustic lenses were constructed with a more superficial focus and a minimal beam width at focus depth. By adding the lens to the US transducer, the focus depth was shifted to the depth of the target.

The newly constructed lenses consisted of Polymethylpentene (TPX), a thermoplastic polymer that can be moulded into any desired shape. The TPX study lens consisted of two lenses. The radius of the transducer (8 mm) was carved out of the plastic to make the lens fit onto the
transducer itself, and on the other side, lenses with different radiuses were carved out. For comparison, a placebo acoustic lens was constructed with the transducer radius but without the carved lenses on the other side. (Supplementary Fig. 1).

Using the lens makers’ formula, the radius of the focusing lens was calculated:

\[
\frac{1}{f} = (n - 1) \left[ \frac{1}{R_1} - \frac{1}{R_2} + \frac{(N-1)d}{nR_1R_2} \right]
\]

Supplementary Table 1 displays the characteristics of various lenses with different radiuses. Lens 2 with the 3 mm radius reduced the focus depth to 6.5 mm, with a decrease in beam width of 60%. Lens 3 with a 2 mm radius decreased the focus depth to 5.5 mm, with the same decrease in beam width. To keep the both the acoustic and the placebo lens in place during scanning, a lens holder device was 3D printed. (Supplementary Fig. 1c).

The output of the probe with the additional lenses was measured with the hydrophone. Results are displayed in Fig. 4c. As the lens with the 3 mm radius already decreased focus depth to 4.5 mm, this lens was considered suitable for the experimental task in which the target structure was located at that depth. The focus depth was decreased from over 10 mm to 4.5 mm from the transducer surface, with a decrease in elevational resolution of approximately 60%, corresponding to a beam width of slightly less than 0.4 mm.

2.3. Experiment
A simulated peripheral vein cannulation study was performed comparing the performance of volunteers with and without the additional 3 mm radius lens. The study protocol was approved by the Medical Ethics Committee United (MEC-U, Nieuwegein, the Netherlands) with reference number nWMO-2019.097.

2.4. Participants
Participants were recruited from the staff of the operating room and intensive care unit of the Catharina Hospital Eindhoven. Participants either had experience with ultrasound guided vascular access procedures (anesthesiologists or intensivists) or had no experience (less than 5 procedures) with these procedures (anesthetic nurses). Written informed consent was obtained from all participants prior to the start of the study.

2.5. Study endpoints
The primary endpoint of the study was first pass success, defined as a correct intravascular placement of the intravenous cannula in one puncture.

Secondary endpoints were as follows:
Output colours: acoustic signal highest-lowest yellow-orange-green-light blue; dark blue: no acoustic signal.

The elevation plane is at approximately 4.5 mm

Y-axis: width of US plane (elevational thickness).

X-axis: increasing depth from transducer.

c. The slice thickness (transducer elevation along the y-axis) is clearly reduced with the acoustic lens from roughly 1.5 mm to 0.75 mm (50% reduction). The focus of

b. L12

At a depth of 5 mm, the elevation thickness is approximately 1.5 mm (red arrow)

a. L15-7io vascular probe; The focus of the elevation thickness plane lies clearly at a point at approximately 10 mm depth (red asterisk)

Fig. 4.

- total number of punctures (defined as new skin breaks)
- needle withdrawals >5 mm without leaving the vascular phantom
- needle visibility, assessed on a 5-point Likert scale, with 1 indicating that the needle was not visible during the entire procedure and 5 indicating a perfectly visible needle throughout the procedure

2.6. Procedure

Before performing the intravenous cannulation, participants received a brief explanation about the goal of the study. The procedures were performed with a US phantom (Brachy 4-vessel ultrasound training block model, Blue Phantom, Redmond, WA, USA). Inexperienced users were familiarized with the phantom and performed practice US-guided punctures as desired. The inserted intravenous catheter (Venflon Pro Safety BD infusion therapy AB, Helsinborg, Sweden) was sized 20 gauge (0.9 mm). A superficial vascular structure was identified at a depth of approximately 5 mm.

All participants performed a cannulation with the placebo lens and the focusing acoustic lens, in varying order, in the long axis plane. The procedure was timed, starting from the moment the needle broke the phantom, and ending at the moment the participant indicated that the needle was placed intravascularly. Subsequently, the probe was turned 90 degrees to obtain a short-axis view of the vessel to determine whether the needle was placed intra- or extravascularly. In case of extravascular placement, the participant was asked to reperform the procedure. Again, the timer was started and stopped at the same time points, and this was continued until successful intravascular placement. An observer, blinded to the lens allocation, recorded all endpoints on a case record form. Additionally, all US-guided punctures were stored on the US machine for offline analysis (needle visibility).

2.7. Statistics

As the beam width artefact was not investigated before, an a priori sample size calculation was not possible. Earlier vascular access studies in phantoms included at least 40 pairs of observations [9-11] Therefore, we included as many participants as were available at our department during the study days. All analyses were performed using SPSS (version 27.0, SPSS Inc., Chicago, Illinois, USA). Data were assessed for normality with the Kolomogorov-Smirnov test. If a normal distribution was found, paired continuous variables were analysed with a paired t-test and categorical variables with the McNemar test. For non-normal distributed data, the Wilcoxon signed rank test was used.

3. Results

In total, 67 participants were included in this study, 36 of whom were naïve to ultrasound guided vascular access procedures and 31 were experienced US users (>100 US guided punctures). First pass success with the acoustic lens was 61 out of 67 (92.5%). With the placebo acoustic lens, the primary outcome of a successful puncture at the first pass occurred in 46 of 67 punctures (68.7%, difference 23.8%, 95% confidence interval 11.0–35.3%, p < 0.001) To illustrate the effect even more, 18 participants succeeded on the first pass with the acoustic lens but failed with the placebo lens, in contrast to only 2 participants who had success with the placebo lens but missed with the acoustic lens.

Regarding the secondary endpoints, the number of punctures needed for successful placement of the cannula was significantly higher in the placebo lens group (1.1 vs 1.4, difference 0.27, 95% CI 0.11 to 0.43 p = 0.002). No differences were found in procedure time, needle withdrawals of more than 5 mm, needle visibility or operator satisfaction. All results are displayed in Table 1.

Notably, the first pass success rates with and without the acoustic lens were not different between the experienced and inexperienced users (acoustic lens 93.5% versus 91.7%, difference 1.8%, 95% CI of the difference –2.83–1.45%, p = 0.770; placebo lens 74.1% vs 67.7%, difference 7.5%, 95% CI of the difference –15.3–12.4, p = 0.502).

4. Discussion

In this study, we explained and demonstrated the impact of elevation thickness and the resulting beam width or slice thickness artefact in superficial ultrasound-guided vascular access procedures. Our results show that the success of these procedures is significantly improved by
using an acoustic lens that decreases the width of the US beam and focus depth.

The beam width or slice thickness artefact is a well described phenomenon, but it is hardly known amongst users of US [1,2]. (Fig. 2). In pediatrics, the presence of the artefact is recognized but the mechanism is not described comprehensively. The effect of the beam width artefact is greater above or below the focus depth, as the beam width is greater there than at the focus depth. The focus of most commonly used US probes is deeper than superficial structures such as peripheral veins or the radial artery, rendering these probes in fact ‘out of focus’. Consequently, for superficial procedures special probes should be used, just as one would use special glasses for reading a book.

In our phantom study, we placed an additional focusing lens on the US transducer, which decreased the focus depth as well as the elevation width to the depth at which the vascular structure in our model was situated. In our simulations and real time measurements of the acoustic output of the transducer, the lens achieved the desired reduction in focus depth and beam width. In the experiment, inexperienced as well as experienced US users had significantly less difficulty establishing vascular access on the first pass with the extra focus of the acoustic lens than without it. Stated otherwise, the optical illusion of intravascular needle placement, despite a clear extravascular position of the needle in the short axis, occurred 20 times without the additional focusing lens, compared to 5 times with our lens. Our finding of a success rate of 68.7% without the use of the additional focusing lens is in line with the findings of previous randomized clinical trials regarding this subject, which reported success percentages of in-plane vascular access procedures ranging between 68 and 85% 4-6, 13, 14. In contrast, use of the additional focusing lens increased this rate to 92.5%.

The higher success rate with the lens was consistent in both the experienced and the inexperienced group, and also the failure rate with the placebo lens was similar between the experienced and inexperienced users. Notably, well-trained anesthesiologists performed 7 failed attempts on the first pass in a simple vascular phantom. This suggests the beam width artefact cannot be overcome by experience. Presumably this also explains why the in-plane approach, which is claimed to provide better visualization of the position of the needle tip, fails to demonstrate superiority over short axis procedures, even if performed by competent US users 14.

A potential drawback of the additional focusing lens could have been a greater difficulty in visualizing the needle, as the smaller beam width might have made it more difficult to align the probe and the needle. However, operator satisfaction and needle visibility did not differ between the punctures with the placebo lens and the actual acoustic focusing lens. Therefore, technical improvement of ultrasound probes and lenses intended for superficial procedures is possible without compromising image quality or usability.

In clinical practice, the findings of the present study can be used to improve the success rate not only for vascular procedures but also for biopsies of superficial tissues such as breast or thyroid tissue, as the same ultrasonic principles apply. Additional focusing of the US lens can prevent superficial targets from being missed, while the correct needle position seems to be confirmed by ultrasound, which may lead to incorrect pathological diagnoses.

This study has several limitations. First, a phantom study does not represent all variables of a real clinical setting. However, the physics are the same, and it is likely that the advantages of the better focused transducer-lens combination would have been even more obvious in the more complex clinical patient setting. Second, the setup used was slightly cumbersome in use and therefore not suitable for clinical studies, as the addition of 3D-printed lens holder made the ultrasound probe bulkier. Additionally, copious amounts of ultrasonic gel were required to prevent air intervening with good visualization. For a clinical test, the lens should be incorporated in the ultrasound probe itself.

5. Conclusion

Our study demonstrated that an additional focusing lens decreases beam width and thereby reduces the beam width artefact, resulting in a significantly higher first-pass success rate for ultrasound-guided simulated peripheral vascular cannulation. We demonstrated that this beam artefact is a real problem for both inexperienced and experienced US users. Future research should determine whether additional focusing of ultrasound probes intended for superficial procedures can improve the accuracy of vascular access procedures as well as other ultrasound-guided needle-based interventions in clinical practice.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclinane.2022.110666.

Table 1
Results.

| Parameter               | Acoustic lens | Placebo lens | Difference (95% CI) | p       |
|-------------------------|---------------|--------------|---------------------|---------|
| First pass success (%)  | 92.5          | 68.7         | 23.9 (11.0 to 35.3) | <0.001  |
| Procedure time (s)      | 11.5          | 16.3         | 4.7 (~0.2 to 9.5)   | 0.065   |
| Punctures               | 1.98          | 1.377        | 0.27 (0.11 to 0.43) | 0.002   |
| Needle visibility       | 0.11          | 0.17         | 0.066 (~0.19 to 0.285) |       |
| Needle visibility       | 3.7           | 3.5          | 0.15 (~0.16 to 0.305) |       |
| Operator satisfaction   | 4.1           | 3.9          | 0.19 (~0.10 to 0.238) |       |

Data are expressed as mean or as * median (25th–75th percentiles). P-values for continuous data are based on paired t-test for normally distributed data and Wilcoxon Signed Ranks test for non-normally distributed. For % measures McNemar test was used. P values < 0.05 are considered significant and marked in bold.

Author contributions

TH, EK and MdW performed calculations and simulations with the acoustic lenses, and revised the manuscript for important intellectual content. HJS initiated the study, collected data and drafted the manuscript. HJS revised the manuscript for important intellectual content. RAB and HHMK conceptualized and designed the study and revised the manuscript for important intellectual content. YH, TH, EK and MdW performed calculations and simulations with the acoustic lenses, and revised the manuscript for important intellectual content.

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Declaration of Competing Interest

RAB and HHMK have acted as clinical consultants for Philips Medical Research, Eindhoven, the Netherlands since January 2016. All other authors declare no competing interests.

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