doi:10.1111/anae.13921

Review Article

Improving needle tip identification during ultrasound-guided procedures in anaesthetic practice

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Summary
Ultrasound guidance is becoming standard practice for needle-based interventions in anaesthetic practice, such as vascular access and peripheral nerve blocks. However, difficulties in aligning the needle and the transducer can lead to incorrect identification of the needle tip, possibly damaging structures not visible on the ultrasound screen. Additional techniques specifically developed to aid alignment of needle and probe or identification of the needle tip are now available. In this scoping review, advantages and limitations of the following categories of those solutions are presented: needle guides; alterations to needle or needle tip; three- and four-dimensional ultrasound; magnetism, electromagnetic or GPS systems; optical tracking; augmented (virtual) reality; robotic assistance; and automated (computerised) needle detection. Most evidence originates from phantom studies, case reports and series, with few randomised clinical trials. Improved first-pass success and reduced performance time are the most frequently cited benefits, whereas the need for additional and often expensive hardware is the greatest limitation to widespread adoption. Novice ultrasound users seem to benefit most and great potential lies in education. Future research should focus on reporting relevant clinical parameters to learn which technique will benefit patients most in terms of success and safety.

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Accepted: 23 March 2017
Keywords: regional anaesthesia: mechanism of injury; ultrasonography: internal jugular; ultrasound structures: echogenicity

Introduction
The use of ultrasound (US) has made a major impact on the performance of needle-based procedures in anaesthetic practice [1]. Ultrasound guidance has been shown to increase the safety and success of central venous cannulation [2, 3] and improves success rate and block quality while reducing occurrence of systemic toxicity for peripheral nerve blocks [4–6]. However, failures and complications during vascular access procedures can still occur leading to serious morbidity [7, 8]. Likewise, the use of US has not eliminated intraneural needle placement or reduced the incidence of postoperative neurological symptoms after regional anaesthesia [9–12]. These probably relate to

one of the most commonly made mistakes during US-guided procedures: advancing the needle without seeing the needle tip properly [13]. Probe handling is challenging because of the dynamic nature of US and, therefore, requires extensive practice [14, 15].

Both in-plane and out-of-plane approaches impose the risk of accidentally damaging structures not visible on the US screen [16]. Furthermore, as the needle tip and the nerve are in close proximity, small unintentional movements can easily lead to nerve penetration [17].

A variety of technologies are available that may help to align the needle and the US beam or facilitate a clear view of the needle tip, from simple mechanical devices to advanced automated needle-detection software. As many of these new techniques were originally developed for other purposes such as liver or breast biopsy, anaesthetists might not be familiar with them. Therefore, we performed a scoping review to give guidance on techniques to improve needle tip visualisation in when using US.

Methods

A great variety of technologies have been tested in different study designs, both in phantoms as well as in patients and with varying outcome measures, such that conducting a systematic review was not feasible. We also anticipated encountering techniques we were unaware of beforehand, forcing us to redefine our search strategy. Therefore, a scoping review seemed most appropriate to rapidly map the key concepts and examine the extent, range and nature of research activity [18, 19]. Pubmed, Web of Science, the SPIE Digital Library and IEEE Xplore were searched with combinations of the following search terms: 'Ultrasonography'[Mesh] or ultrasound; needle tip, tracking, alignment, segmentation, detection, identification or visualisation; robot*, image fusion, needle guide, laser, optical tracking, augmented reality, magnet*, electromagnet*, GPS, radiofrequency, 3D or 4D; (loco)regional, epidural, spinal or neuraxial anaesthesia or nerve block; vascular puncture or access, central venous catheterisation or cannulation, arterial catheterisation or cannulation. The search was limited to articles published in English until March 2017. Two authors (HS and AB) independently assessed eligibility for inclusion in the review, with the final decision based on consensus. Additionally, 'grey' literature such as clinicaltrials.gov and the FDA devices database, as well as the selected reports, were screened for additional references. Phantom studies, case reports and series were also considered for inclusion.

Results

The results of our search are shown in Fig. 1. After screening an initial 5441 citations, 107 studies were included. A considerable part of excluded studies covered two-dimensional (2D) US without additional needle visualisation techniques. Furthermore, studies regarding prostate, breast and liver procedures were considered outside the scope of this review because of differences in probes, targets and depth of procedures. In Table 1, the different technologies are listed and quality of the studies graded according to recommendations by the Oxford Centre for Evidence-Based Medicine [20].

Echogenic needles [21], beam steering [22] and compound imaging [23] have been shown to increase needle visibility but, as they do not specifically aid in

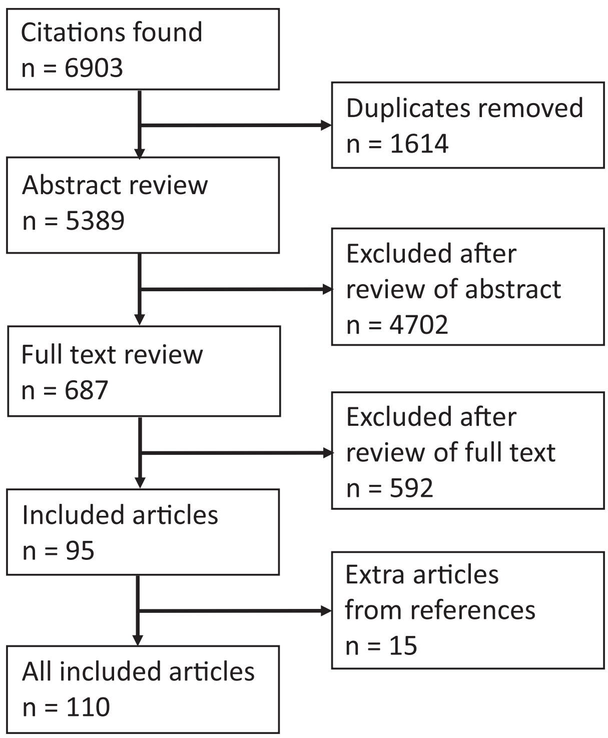

Figure 1 Overview of literature search results.

Table 1 Levels of evidence for available needle and needle tip visualisation technologies according to the 2011 Oxford Levels of Evidence [1]

Needle guides	
Improve visibility of the needle during US procedures	Level 3
Reduce performance times of US guided procedures	Level 3
Increase self-reported ease of US guided procedures	Level 3
Do not reduce adverse events	Level 3
Needle (tip) design	
Vibrating needles improve needle visibility in models	Level 4
The photoacoustic effect can aid needle tip recognition	Level 4
Needle tip sensor technology allows needle detection at greater depth and steeper angles	Level 4
3D/4D ultrasound	
No benefit in vascular or regional anaesthetic procedures is reported	Level 4
Can be used to monitor spread of local anaesthetic	Level 4
Can be used to identify catheter malpositioning	Level 4
Can be used to determine epidural puncture insertion site	Level 4
Leads to lower resolution and frame refreshment rates compared to 2D imaging	Level 4
Optical tracking	
May predict needle trajectories with acceptable accuracy	Level 4
Loses reliability if the needle bends	Level 4
Augmented reality	
Demonstrates excellent qualities for training inexperienced sonographers	Level 3
Reduces performance times and needle redirections in models	Level 3
May facilitate spinal interventions	Level 4
Robotic assistance	
Can improve stability of probe handling during US procedures	Level 4
Combined with an infrared camera may enable automated venepuncture	Level 4
Image based needle tracking	
Subtracting US images can aid in monitoring needle advancement	Level 4
Pixel classifying algorithms can predict needle tip position with great accuracy	Level 4
Image based algorithms can identify nerves and blood vessels as well as needles	Level 4
Acoustic Radiation Force Impulse may allow needle tip recognition at greater depths and steeper angles than conventional US	Level 4
Electromagnetic tracking	
Reduces duration and needle redirections for out of plane approaches	Level 3
Improves needle visibility during in plane approaches	Level 3
Gives inexperienced sonographers a steeper learning curve	Level 3
May facilitate spinal and epidural punctures	Level 4
Magnetism	
May facilitate central venous catheterisation	Level 4
May decrease adverse events related to central venous catheterisation	Level 4
Reduce performance times and needle redirections in models	Level 3

aligning probe and needle or in identifying the needle tip, these techniques are not addressed in this review.

Needle guides

These (Fig. 2) are attached to the US probe to maintain the needle strictly within the US plane. Most allow multiple angles of insertion, modestly improve the proportion of time the needle is visible and reduce time needed to perform different tasks in gelatin phantoms [24–27]. The effect is most pronounced in inexperienced participants during out-of-plane approaches [28–30]. The Infiniti Plus™ (CIVCO Medical Solutions, Kalona, IA, USA) is the most frequently described guide and has been used in over 100 successful jugular and subclavian venous catheterisations. Additional assistance for guidewire introduction is sometimes needed and arterial punctures still occur [31, 32]. In more than 400 jugular vein cannulations,

Figure 2 Example of a needle guide attached to an ultrasound probe (Image courtesy of Civco, Kalona, IA, USA).

sonographers achieved higher first-pass success rates compared with freehand scanning, but carotid punctures occurred equally in both groups [33]. Needle guidance reduces time to perform supraclavicular nerve blocks or femoral nerve catheter placement, but this does not improve patient satisfaction or success rate [34, 35]. Finally, guidance can aid spinal punctures using a paramedian approach [36].

Lasers attached to the US transducer can aid needle alignment by projecting a line corresponding to the US plane on the surface (Fig. 3). Two different devices reduce puncture time in phantoms [37–39]. As the laser only projects the plane on the surface of the model, it is still possible to leave the plane after the needle has penetrated the skin.

In summary, mechanical needle guides enhance needle visualisation, modestly shorten procedure times and increase success rates. Inexperienced users seem to benefit more, so needle guides can aid training. Drawbacks include limited degrees of freedom, thus hindering attempts at multiple targets within one puncture or impeding probe or needle adjustment in response to patient movement. Most guides are disposable, increasing costs. Unfortunately, needle guides do not seem to reduce complications such as carotid puncture.

Needle (tip) design

Technical alterations to the needle (tip) may facilitate sonographic recognition. Adding a piezo crystal to the needle to create vibration at the tip enabled its detection using colour Doppler in a cadaveric study [40]. Placing a small actuator at the needle tip serves the same purpose but the intended interference with the acoustic signal also generates artefacts that can

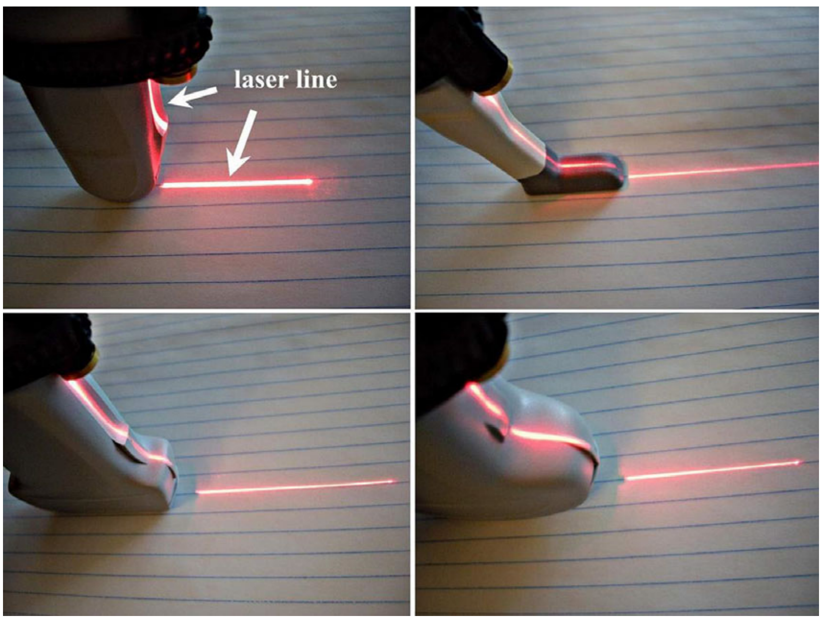

Figure 3 Example of a laser guide attached to an ultrasound probe (Image courtesy of Regional Anesthesia and Pain Medicine through Copyright Clearance Centre license number 3951950371101).

obscure the image [41]. A longitudinally vibrating needle through an actuator at the needle base generates less artefacts in a model, although no exact results have been reported [42]. After sending a laser beam through an optical fibre placed inside a needle, the photo-acoustic effect will convert this light into acoustic energy. The generated sound waves leak through the needle tip, allowing detection of the tip location using a standard US transducer [43]. Another approach is to calculate the position of sensors placed at the needle tip, relative to the transducer, using the delay in receiving US beams. For this purpose, piezo crystals, a fibre-optic hydrophone (an 'underwater' microphone) placed through the needle, or co-polymer sensors can be used [44–46]. These sensor tip technologies all show good signal-to-noise ratios in swine models, permitting their use at relatively large depths and steep insertion angles.

For most of these techniques, the greatest benefit is likely to be in out-of-plane approaches as the needle shaft and the tip can now be discriminated. The difficulties in needle and transducer alignment are not completely resolved. Specialised needles or catheters are needed and clinical trials are lacking. Additionally, Doppler imaging can reduce US frame rate and image quality.

3D/4D ultrasound

Two-dimensional imaging is the conventional US mode. Three-dimensional US (3D) provides multiple planes: a longitudinal, cross-section and overview plane parallel to the transducer surface. Another option is to compose all acquired data in a rendered volume. Potentially, this provides more detailed information about the position of the needle, the tip and surrounding structures (Fig. 4). Four-dimensional (4D) US refers to real-time 3D imaging. Several techniques/methods exist to perform 3D/4D imaging.

Freehand scanning of a certain region by moving a tracked 2D probe allows reconstruction of a 3D data set (the rendered volume) but only after scanning is complete, which obviously excludes real-time procedures. Still, catheter malposition or distribution of local anaesthetic after nerve blocks can be seen [47, 48].

Mechanically steered probes use a motorised 2D transducer which is continuously swept backward and forward over the region of interest. The time required for data acquisition and reconstruction translates into low-frame refreshment rates and visible pauses. Nevertheless, a simple radial nerve block can be performed [49]. Additionally, 4D US facilitates insertion of epidural catheters in cadavers at levels where an acoustic

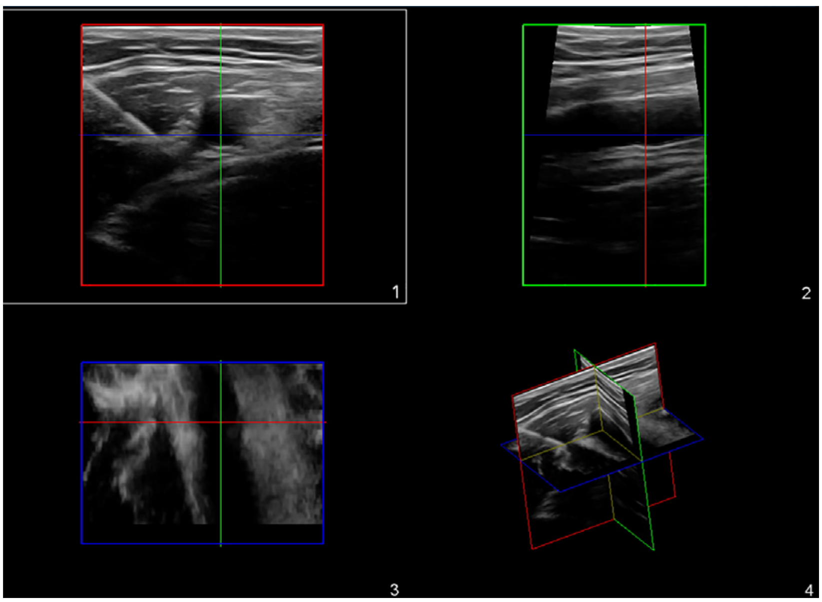

Figure 4 Three-dimensional US image of an axillary brachial plexus block. 1) Longitudinal plane with needle in-plane, cross-section of axillary artery. 2) Cross-sectional plane with axillary artery longitudinally sectioned. 3)'Overview' plane with the axillary artery in sagittal view. 4) Multiplanar, 3D-reconstruction of planes 1–3.

window between the vertebrae is difficult to obtain [50]. In clinical practice performing a 4D US-guided epidural catheter insertion requires a second anaesthesiologist to maintain sterility [51]. Combining 3D US scanning with a specific needle guide (Epiguide, Starfish Medical, Victoria, Canada) helps determine the preferred epidural insertion point, but no punctures have been described yet [52].

Newer matrix array probes use electronic beam steering, allowing faster frame rates and enabling real-time procedures (Fig. 5). Matrix array probes have been used in axillary plexus block [53], catheter placement at the popliteal nerve [54], interscalene [55] and infraclavicular brachial plexus blocks [55, 56]. Even a transoesophageal 3D matrix array probe, providing an anterior view of the spinal cord, can guide placement of an epidural catheter [57]. For central venous access, two reports using 3D/4D US are available, one with a dual view of the short and long axis, the other with a 4D-rendered volume as the main view [58, 59].

All reports note lower image quality and frame refreshment rates (more markedly for mechanical steered probes) using 3D/4D US compared with regular 2D US. Mechanically steered probes lag in real-time procedures and matrix arrays generally have lower resolution [60]. Increased complexity of image acquisition and difficult interpretation of the images are further limitations. An additional drawback is that mechanically steered probes are bulkier, limiting manoeuvrability. Monitoring of the spread of local anaesthetic and improved anatomical orientation are the most cited benefits.

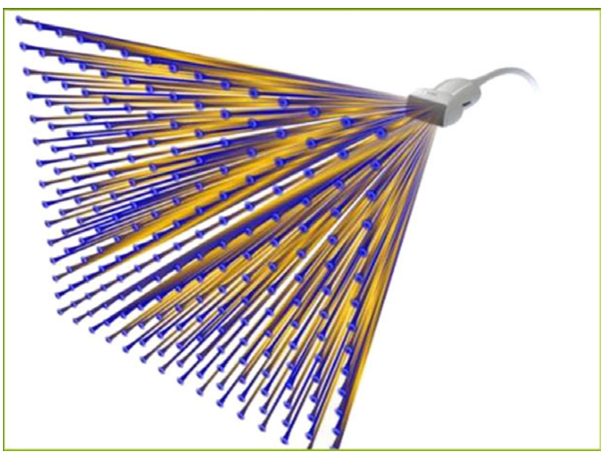

Figure 5 Matrix array 3D/4D US probe (Image courtesy of Philips Research, Eindhoven, the Netherlands).

Electromagnetism

An external field generator creates a magnetic field that induces a small current in specialised sensors attached to the probe and needle. The direction of the current can be used to estimate needle position and direction. Next, the extrapolated needle trajectory can be displayed on the screen of the US machine when using an in-plane approach, or the estimated intersection with the needle tip for out-of-plane approaches [61]. In anaesthesia, the most reported EM tracking system is the SonixGPS (UltraSonix, Richmond, BC, Canada) (Fig. 6). It helps both inexperienced and experienced practitioners to reduce the time needed for simulated nerve blocks or vascular punctures [62–66]. In a spinal model, GPS outperformed both 2D and 4D scanning with regard to procedure time and reducing needle redirections [67]. Electromagnetic guidance aided spinal punctures in a case series, particularly using an out-of-plane approach, as well as in a patient who had previous spinal canal surgery [68, 69].

A Vancouver-based research group described different case series using the SonixGPS for spinal punctures [70, 71], brachial plexus blocks [72, 73] and thoracic paravertebral blocks [74, 75], first in cadavers

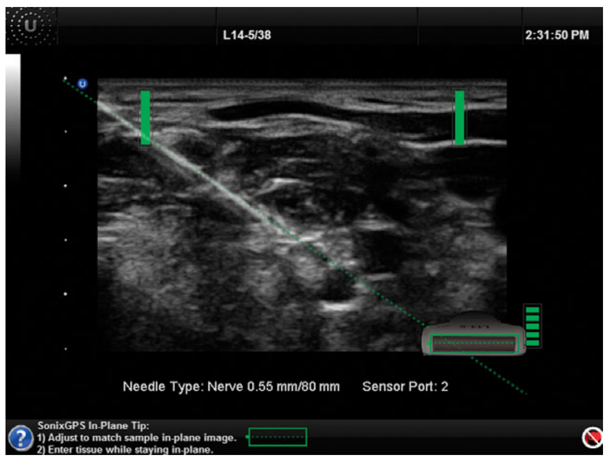

Figure 6 Example of an interface of an electromagnetic tracking system. Example of the predicted needle trajectory using an in-plane technique. In the right bottom of the screen, the orientation of the needle relative to the US probe is shown (Image courtesy of BK Ultrasound, Richmond, BC, Canada).

and subsequently in patients, without complications. During simulated central venous cannulation, the SonixGPS did not reduce performance time or number of attempts compared with freehand US but it alleviated mental workload [76]. Based on their own observations, this group stated that novices profit most from electromagnetic tracking, particularly during out-of-plane approaches [77].

The Etrax (CIVCO Medical Solutions, Kalona, Iowa) uses sensor-enhanced trocars which can contain different kinds of needles and has been tested in cadavers for spinal procedures and in a phantom for biopsies [78, 79].

Interestingly, electromagnetic tracking can be used to register differences in hand motion by adding trackers to the hands of participants. During simulated vascular access and neuraxial blocks, the Drivebay system (Ascension, Burlington, USA) is able to differentiate novices and experts, and to monitor learning progress [80–82]. Analysis of hand motion and needle trajectory is performed using Perk Tutor software (Fig. 7) [83].

Again, electromagnetic needle tracking especially aids novice sonographers but more experienced anaesthetists may also benefit, mainly during out-of-plane needling. An opportunity lies in guidance for neuraxial punctures, where the out-of-plane approach avoids the steep imaging angles and poor needle visibility associated with in-plane approaches. Maybe the greatest potential for electromagnetic tracking lies in education and training. Clinical evidence demonstrating patient benefit is rare.

A drawback is the need for larger needles for adequate visualisation. Accuracy was not reported in most studies but can easily be compromised by increasing the distance of the field generator from the patient or interference from metallic objects [84]. This necessitates placement of the field generator in close proximity of the region where the procedure is performed, possibly disrupting workflow [61]. A small

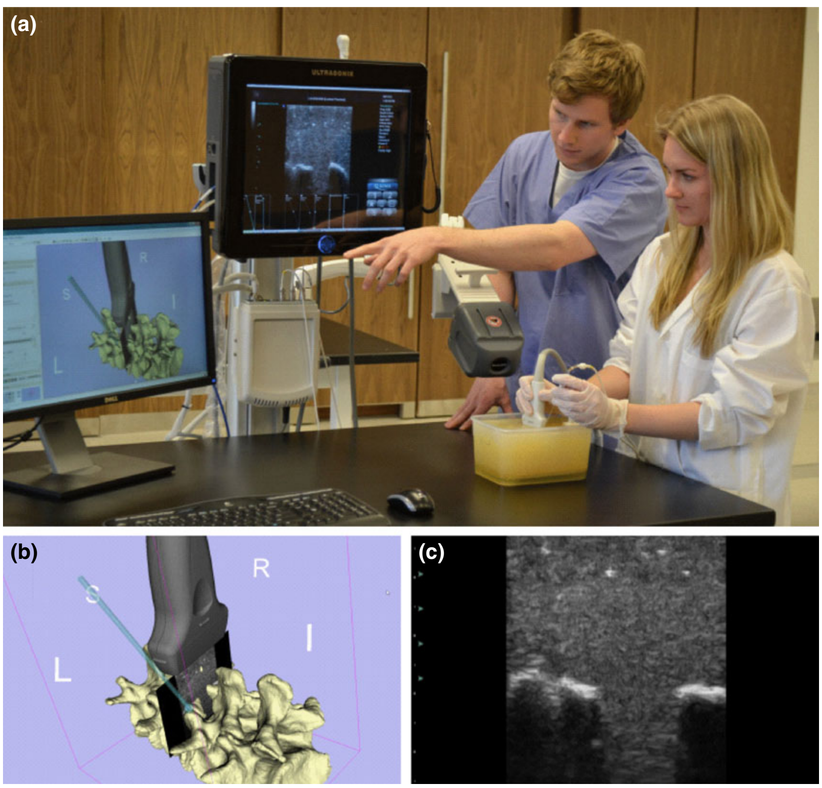

Figure 7 Perk tutor interface. a) System set-up with phantom, electromagnetic tracking system and interface. b) Interface showing fusion image of spine and needle position. c) Ultrasound image (Image courtesy of IEEE through Copyright Clearance Centre, license number 4063760147717).

field generator that can be mounted on the US probe, avoiding this limitation, has only been tested in a gelatin phantom [85]. Lastly, 3D probes seem to generate more electromagnetic interference than conventional 2D probes [86].

Magnetism

After magnetisation of needles, transducers equipped with magnetic sensors can keep track of the needles if they remain close to the transducer, eliminating the need for external field generators. The predicted needle trajectory can be displayed on the US interface, aiding accurate tip positioning. The only human study used the Axotrack (Soma access systems, Greenville, SC, USA), a pistol-like US probe with integrated needle guide and magnetic sensors, in 50 central venous punctures (Fig. 8) [87] . Inexperienced participants using the Ezono 4000 (Ezono AG, Jena, Germany) needed fewer out-of-plane attempts, shorter procedure times and made significantly less posterior wall and carotid artery punctures in simulated internal jugular vein cannulation [88–90]. A recently developed prototype by General Electric (Wisconsin, USA) uses passive magnetic characteristics of commercially available needles, omitting the magnetisation procedure and, thus, improving workflow. Both inexperienced and experienced users performed procedures (especially out of plane) with a higher success rate and better accuracy [91, 92]. Magnetic guidance seems a promising feature for US-guided procedures, although specialised probes are still necessary and needles must be magnetised or otherwise prepared before use. Larger clinical studies are needed to determine the value of this technology.

Figure 8 Axotrack™. Example of the pistol-like Axotrack™ (Soma Access Systems, Greenville, SC, USA) (Image courtesy of Sonosite, Bothel, WA, USA).

Optical tracking

The position of the US transducer and needle relative to each other can be tracked using camera recordings. Using the recorded images, the predicted needle path can be displayed on an overlay on the US screen, analogous to the principle of electromagnetic tracking (Fig. 9). Different set-ups have been developed with one or more cameras attached to stand-alone frames or even to the US probe. There are few proper trials but accuracies in needle tip detection (as measured in root-mean-square error, ranging from 1 to more than 6 mm) have been reported [93–95]. Shorter procedure times and less accidental nerve or vessel damage were reported in a phantom when compared with freehand punctures [96]. As a low-cost solution, the Microsoft Kinect (Microsoft corporation, Redmond, WA, USA), normally used for gaming, can aid in identifying needles [97]. Another opportunity for optical tracking is to reconstruct 3D images, for instance of the spine, to determine a desired epidural puncture site [98].

Figure 9 Optical tracking system. Example of the Clearguide One tracking system using two stereo cameras attached to the ultrasound probe (Image courtesy of Clear Guide Medical, Baltimore, MD, USA).

The robustness and accuracy of optical tracking are roughly equal to electromagnetic tracking but some studies report rather large errors (over 5 mm), possibly caused by bending of needles under the surface as needle trajectory is calculated based on the needle path outside the target. Higher costs and the need for direct and unobstructed vision of the probe and needle are disadvantages. We are not aware of clinical studies using optical tracking in anaesthesia, apart from imaging regions of interest [98].

Image fusion/augmented reality

By calibrating tracked instruments and US probes with pre-recorded data from other imaging modalities (CT, MRI), an augmented reality environment can be constructed. This can be assessed real-time with US, allowing determination of structures in the US image. Most systems use electromagnetic tracking for navigation. A very simple system consists of a micro-projector attached to the US probe, displaying the US image on the skin of a vascular phantom directly adjacent to the edge of the probe [99].

A system combining EM tracking (Aurora, Northern Digital, Waterloo, Canada), a virtual 3D data set constructed from spinal CT images (Atamai Viewer, Calgary, Canada) and a 3D printed spine model has been developed for practising facet injections and lumbar punctures [100, 101].

A research group from Ontario, Canada also created an augmented reality environment for practising spinal interventions using different electromagnetic tracking systems (Aurora, SonixGPS or Drivebay). After acquiring US images, the desired needle insertion point and trajectory can be calculated using the open-source Perk Tutor software [83], and displayed as a laser overlay on a phantom of the spine. An interesting feature of this system is a dual view of both short- and long-axis images. Inexperienced sonographers benefited from training with the system for facet joint injections and difficult spinal punctures [102–105].

Instead of a pre-procedural scan, a statistical spine model based on a series of CT scans of unique patients or MRI images can be used for real-time 3D anatomical reconstructions that could potentially benefit facet blockade or central venous cannulation [106, 107]. The only clinical study in anaesthetic practice used electromagnetic tracking (Northern Digital) in combination with PercuNav image fusion (Philips Healthcare, Bothell, USA) to plot a desired needle path based on pre-recorded CT or MRI images for injections to the piriformis muscle in five patients [108].

In conclusion, fusion of different imaging modalities allows better anatomical orientation in the patient, e.g. for differentiation between epidural or spinal levels. This can potentially benefit needle placement, particularly in cases where bony structures hinder US scanning. However, needle tip location is not good and nerves or vessels can still be punctured. The need for pre-procedural CT or MRI reserves the use of fusion techniques mostly for chronic pain interventions, though using statistical data sets of spinal anatomy may circumvent this drawback. The greatest benefit seems to be in creating simulated environments for educational purposes.

Image-based needle tracking

Instead of using external hardware for identifying and displaying needles and their trajectories, software can detect needles using advanced image processing algorithms. A straightforward method subtracts subsequent US images from each other, with the calculated differences providing clues to needle advancement or movement. However, it requires jiggling or other motion of the needle, movement of a stylus inside the needle or vibrations caused by the natural tremor of the sonographer's hand [109–111]. Combining analysis of tissue deformities in front of the moving needle with the subtraction algorithm achieves submillimetre accuracy [112]. Using tracked freehand 3D scanning with vibrating needles, power Doppler analysis permits exact calculation of needle trajectories [113].

Another algorithm uses circular US waves, created by sequentially firing crystals in the transducer. The delay in the returning waves can be used to calculate needle trajectory with high accuracy [114].

More advanced needle detection algorithms use pixel characteristics to differentiate between needle and tissue. Most assume that the needle exhibits the brightest pixels in the image; furthermore, they identify linear structures (Radon and Hough transform), filter-specific transitions of bright and dark pixels (Gabor filter) and can eliminate outliers based on statistical probability (Kalman and RANSAC). In 2D scanning, detection of the needle angle allows the US beam to be perfectly steered for needle visibility enhancement [115]. If combined with 3D scanning, automated needle detection algorithms do not require perfect alignment of needle and probe, addressing the problem of unintentional probe manipulation during interventions. Although some are time-consuming, they detect the needle tip with high accuracy [116–119]. Interestingly, the same algorithms can be trained to detect other linear structures such as nerves and blood vessels, which allows for the ideal needle trajectory of entry to be calculated for median or femoral nerve blocks [120, 121].

Lastly, acoustic radiation force impulse (ARFI) can distinguish needle and tissue based on the mechanical response of different tissues to the US wave, which can be detected using a normal US transducer. It specifically aids in out-of-plane approaches or very steep angles [122].

In conclusion, needle detection algorithms show promise in models. However, it remains to be seen which algorithms will deliver reliable results when applied to dynamic images in humans where there is more transition in tissue intensities. Additionally, extra hardware is often needed, as the algorithms require powerful computers and most are based on 3D US.

Robotic assistance

Robots can offer advantages such as more stable probe stabilisation, more precise needle handling and at the same time reduce discomfort or fatigue in the sonographer [123]. In a gelatin model, a robotic needle placement unit can perform biopsies of embedded peas with high accuracy using manually-generated US images [124]. A two-robot system, with one robot tracking the needle using Kalman and RANSAC algorithms to guide the needle by the other, reaches a very high accuracy of 1 mm [125]. The Da Vinci Surgical System Robot (Intuitive Surgical, Sunnyvale, CA, USA), normally used for prostate or other abdominal surgery, can also perform a single nerve block and insert a catheter in a phantom, after initial manual positioning of the US probe [126]. The Magellan (ITAG Lab, Montreal, Canada) is a specifically-developed nerve block robot. In a phantom, precision of needle placement is comparable but, not surprisingly, robotic needling is more time-consuming than freehand [127]. After manually identifying the sciatic nerve in 13 patients, the Magellan could accurately place the needle for a successful block (Fig. 10) [128].

Another US-based robotic system has been developed for central venous cannulation but has only been tested with a single puncture in a vascular phantom [129]. For venepuncture, the fully automated Venouspro (VascuLogic, Piscataway, NJ, USA) (Fig. 11) combines US with an infrared camera for detection of veins in the forearm, with a closed loop puncture robot completing punctures in a model with an accuracy under 1 mm [130].

In conclusion, robots have appeared in anaesthesia but clinical experience is limited at present. Procedures

Figure 10 Magellan nerve block system. Figure showing the software interface, joystick and robot arm of the Magellan nerve block system (Image courtesy of *Anesthesia and Analgesia* through Copyright Clearance Centre license number 3951960883910).

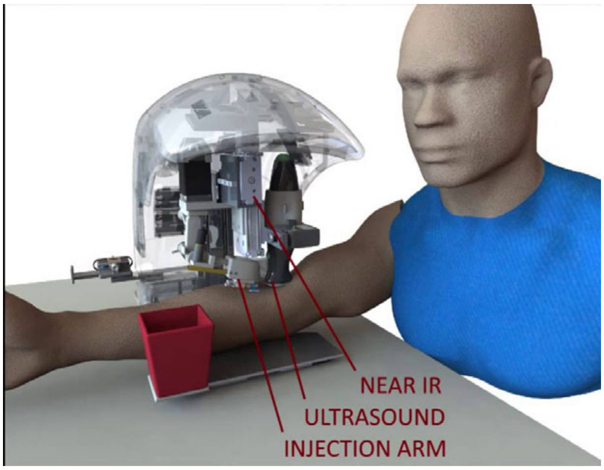

Figure 11 VenousPro™ venepuncture robot. Schematic overview of a venepuncture robot using ultrasound and infrared (IR) camera (Image courtesy of VascuLogic, Piscataway, NJ, USA).

are difficult to learn and time-consuming and, therefore rely, much on operator experience and skill. High cost and low availability are also hindering broader adoption. However, as robots improve in terms of accuracy and stability, their role should expand in the future when technologic advances will enable production of smaller, cheaper and more user-friendly devices.

Discussion

We conducted an extensive literature search for additional techniques that help with aligning needle and probe or identify the needle tip during US-guided procedures in anaesthetic practice. Most of these techniques modestly improve first-pass success rates and reduce performance times, particularly in less experienced operators. However, it needs to be emphasised that most available evidence comes from case reports or series in phantoms and cadavers with few clinical studies reporting improved patient outcomes.

Mechanical needle guides offer some improvement, especially for novice US users and out-of-plane approaches. Magnetic and electromagnetic guidance seem promising but additional costs for specialised needles or probes and environmental interference from metallic objects are current limitations. Fusion of tracked US with CT or MRI images is only feasible when these additional imaging examinations are available. However, augmented reality techniques have shown excellent potential for educational purposes. The added value of 3D and 4D US has still to be demonstrated. Robots can improve stability and accuracy with excellent but expensive needle guidance. Computer-based algorithms have only been tested in vitro.

Possibly, a combination of different techniques will be the key for improvement of needle-based procedures. For instance, optical tracking and robotics have already been combined for renal puncture, and 3D US and vibrating needles can aid robotic needle placement in liver radiofrequency ablation [131, 132]. Moreover, advanced tissue recognising technologies can differentiate nerves, ligaments or even intraneural fascicles using electrical impedance, optical coherence tomography (a specialised fiberoptic laser) or high-frequency US [133–135]. The next step, combining nerve detection with advanced needle trajectory planning, is already in development for femoral and median nerves [120, 121].

Regarding existing technologies, higher resolution and frame refreshment rates, less bulky hardware with greater manoeuvrability and lower costs are the most anticipated future developments and research should focus on these areas. Next, results from clinical trials are necessary to engage anaesthetists and not only inventors and US enthusiasts. That way, these innovations can entice the same widespread adoption and clinical innovation that US itself has gained in the past decade.

In conclusion, US guidance in anaesthetic practice continues its evolution with the development of additional technologies to enhance needle (tip) visualisation. Thorough knowledge of sono-anatomy, a good understanding of US principles and some level of dexterity are still required to perform safe and successful US-guided procedures. Currently, available US adjuncts certainly help in acquiring those necessary skills and, therefore, deserve a place in education and training. Considering recent and future technical developments, it will be interesting to see which needle tip visualisation tool patients will eventually benefit from the most.

Acknowledgements

This investigator-initiated work is part of a PhD study (HS), which is embedded in a research consortium of the Catharina Hospital Eindhoven, the University of Technology Eindhoven and Philips research Eindhoven (IMPULS project). No external funding or competing interests declared.

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