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On the Feasibility of Imaging Peripheral Nerves Using Acoustic Radiation Force Impulse Imaging

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Abstract

Regional anesthesia is preferred over general anesthesia for many surgical procedures; however, challenges associated with poor image guidance limit its widespread acceptance as a viable alternative. In B-mode ultrasound images, the current standard for guidance, nerves can be difficult to visualize due to their similar acoustic impedance with surrounding tissues and needles must be aligned within the imaging plane at limited angles of approach that can impede successful peripheral nerve anesthesia. These challenges lead to inadequate regional anesthesia, necessitating intraoperative interventions, and can cause complications, including hemorrhage, intraneural injections and even nerve paralysis. ARFI imaging utilizes acoustic radiation force to generate images that portray relative tissue stiffness differences. Peripheral nerves are typically surrounded by many different tissue types (e.g., muscle, fat and fascia) that provide a mechanical basis for improved image contrast using ARFI imaging over conventional B-mode images. ARFI images of peripheral nerves and needles have been generated in cadaveric specimens and in humans *in vivo*. Contrast improvements of >600% have been achieved for distal sciatic nerve structures. The brachial plexus has been visualized with improved contrast over B-mode images *in vivo* during saline injection and ARFI images can delineate nerve bundle substructures to aid injection guidance. Physiologic motion during ARFI imaging of nerves near arterial structures has been successfully suppressed using ECG-triggered image acquisition and motion filters. This work demonstrates the feasibility of using ARFI imaging to improve the visualization of peripheral nerves during regional anesthesia procedures.

Keywords

ARFI imaging; nerve; radiation force; regional anesthesia

I. INTRODUCTION

The use of ultrasound image guidance for regional anesthesia has grown significantly over the past five years. The benefits of directly visualizing nerves and needles using ultrasound guidance without having to rely on surface landmarks¹ and nerve stimulation^{2, 3} alone has been documented extensively. The benefits of ultrasonic guidance exist despite several limitations, including relatively poor acoustic contrast between nerves and surrounding tissues in some anatomic locations, limitations on needle orientation and angles of insertion and image distortion during and post-injection. The current state of clinical practice for ultrasonic imaging guidance is to use equipment designed for other specialties, such as cardiology and obstetrics,

and adapt them for clinical use in regional anesthesia. The development of ultrasonic imaging modalities to enhance the visualization of structures specific to regional anesthesia procedures could help improve their efficacy and reduce adverse side effects.

B-mode imaging allows anesthesiologists to visualize peripheral nerves and their adjacent structures while helping prevent inadvertent intravascular or intraneural injections. Ultrasound guidance also facilitates monitoring of the distribution of injected anesthetic around the targeted nerve. B-mode imaging, however, is not without its shortcomings. Nerves can be easy to visualize but there are many occasions when nerves and their surrounding soft tissues have very similar acoustic impedances, leading to poor B-mode image contrast. Additionally, the distortions that take place during the injection of local anesthetic can distort the local anatomy, making nerve visualization difficult throughout the infusion of local anesthetic. The fundamental limitations of B-mode imaging have prompted the study of another ultrasound-based imaging modality that relies on differences in tissue elasticity to generate images with improved contrast to provide better image guidance during regional anesthesia procedures.

Tissue elasticity (i.e., stiffness) is a soft tissue property that often exhibits considerably more variation between tissues than acoustic impedance, providing a mechanism for improving image contrast. There have been many efforts to design stiffness imaging systems that rely on external mechanical excitation as a source of deformation to characterize material properties but these systems face challenges in coupling the excitation (static or dynamic) into the organ/structure of interest. The use of focused acoustic energy to generate transient, micron-scale tissue deformations eliminates this challenge by generating the mechanical excitation in the focal region of the acoustic beam. This phenomenon is the basis for the generation of stiffness imaging systems that utilize acoustic radiation force to mechanically excite tissue in remote locations.⁴⁻⁹

II. METHODS

ARFI imaging

Acoustic Radiation Force Impulse (ARFI) images display information about the relative mechanical properties of soft tissue and have been utilized for a variety of clinical applications, including breast mass imaging,¹⁰ vascular imaging,¹¹ ablation monitoring,^{12,13} pre-operative staging of rectal tumors¹⁴ and prostate cancer imaging.¹⁵ While the focus of these clinical projects involves delineating healthy from diseased tissues based on changes in their stiffness due to their underlying pathology, peripheral nerves have the potential to be delineated from adjacent healthy structures based on their different tissue types (i.e., nerve, muscle, fat and fascia).

Acoustic radiation force is applied to absorbing or reflecting materials in the propagation path of an acoustic wave. This phenomenon is caused by a transfer of momentum from an acoustic wave to the propagation medium. The spatial distribution of the radiation force field is determined by both the transmitted acoustic parameters and the acoustic properties of the tissue. In soft tissues, where the majority of attenuation results from absorption,^{16, 17} the following equation can be used to determine radiation force magnitude:^{18, 19}

$$F=2\alpha I/c \quad (1)$$

where F is acoustic radiation force (in the form of a body force), c is the medium's sound speed, α is the medium's absorption coefficient and I is the temporal average intensity at a given

spatial location. The region of tissue to which radiation force is applied through the absorption of acoustic energy is called the region of excitation (ROE).

Each line in a given lateral location of an ARFI image is generated by transmitting an excitation/pushing beam of acoustic radiation force focused at a defined depth and then the induced dynamic soft tissue displacement response (several microns) is monitored using conventional ultrasonic displacement tracking methods for several milliseconds after cessation of the radiation-force excitation. This process is repeated with an aperture that is electronically translated laterally to fully interrogate the region of interest. The spacing between lateral lines can be controlled, and, utilizing 4:1 parallel receive tracking, the displacement response at four adjacent lateral locations can be tracked simultaneously after a single radiation force excitation, reducing the number of excitation beams that need to be transmitted. When improved contrast is desired in structures that span an appreciable depth, multiple excitations with different focal depths can be performed at each lateral location.²⁰ Displacement images are typically formed at a given time step after cessation of the radiation force excitation and displacement data from different excitation focal zones are spatially averaged.

Imaging configuration

B-mode and ARFI imaging were performed using a Siemens SONOLINE Antares™ scanner (Siemens Medical Solutions, Ultrasound Division, Issaquah, WA) using VF7-3 and VF10-5 linear arrays. The focal configurations used for these arrays are detailed in table 1. To optimize the contrast and spatial resolution of the nerves, multiple focal zone excitations were implemented.²⁰ Typically 2–3 focal zones were implemented; the depths and spacing of these focal zones depended on the range of depths of the structures being visualized. Typically focal zones were spaced by 3–4 mm, with a constant focal configuration (F/#) held between focal zones.

Many peripheral nerves targeted for regional anesthetic injection (e.g., the brachial plexus and femoral nerves) are adjacent to arteries that can introduce significant physiologic motion when tracking ARFI-induced displacements. To minimize such motion artifacts, B-mode and ARFI image acquisitions were ECG-triggered during *in vivo* imaging. Additionally, a linear-motion filter was applied to the tracked displacement data. This motion filter assumes that complete recovery of ARFI excitation-induced displacements occurs within 5 ms of the cessation of the radiation force excitation and any residual displacements that are estimated after this time are secondary to motion. These motion artifacts are assumed to be linear (i.e., no acceleration) given the short time (5 ms) durations.

Displacement estimation and correlation coefficients

Radiation force-induced displacements were tracked using the Loupas' algorithm offline.²¹ ARFI images are displayed using copper color maps in this manuscript, where brighter pixels represent greater displacements away from the transducer and are indicative of relatively more compliant tissue. All ARFI images are displayed at 0.55 ms after the radiation force excitation. This time step was empirically determined to maximize the ARFI image nerve contrast based on their size and stiffness relative to their adjacent tissues after reviewing the cadaveric and *in vivo* datasets.²² A median filter with a 5×2 sample (0.087×0.30 mm) kernel was applied to all of the ARFI images.

The complex correlation coefficient (ρ) associated with the estimated displacements was computed as:²³

$$\rho = \frac{\langle s_1(t)s_2^*(t) \rangle}{\sqrt{\langle s_1(t)s_1^*(t) \rangle \langle s_2(t)s_2^*(t) \rangle}} \quad (2)$$

where $s_1(t)$ represents the reference signal, $s_2(t)$ represents the displacement estimation signal, and $*$ denotes the complex conjugate of the signal. ρ is a complex number whose magnitude denotes the similarity, or overall correlation, of the two complex signals and whose phase represents the phase difference between the two signals. For example, a magnitude of 1 and a phase of 0° indicate perfect correlation while a magnitude of 1 and a phase of 180° indicate negative correlation. Assuming ARFI-induced displacements are in the direction of wave propagation (away from the transducer), the phase varies between $0-90^\circ$ and the magnitude of this complex coefficient represents the correlation between tracking vectors. This magnitude was used to generate the decorrelation maps representing unreliable displacement estimates. Regions of decorrelation ($\rho < 0.98$) are superimposed in blue on ARFI images and represent locations where displacement estimates were not reliable.

Nerve contrast was computed as $1 - D_i/D_o$, where D_i is the mean displacement inside the nerve and D_o is the mean displacement in a similar sized region at the same range of depths outside the nerve. The nerve boundaries (as indicated with dashed circles in the figures) were defined using the ARFI images when the nerves were not readily apparent in the B-mode images.

Cadaveric and *in vivo* human studies

Imaging studies on fresh cadavers were performed in the Human Fresh Tissue Laboratory in the Duke University Medical Center (DUMC). These cadavers were previously frozen and were not formalin fixed. 18G needles were used for saline injections. Image acquisition was not ECG-triggered in the cadaver studies since physiologic motion sources were not present. Motion filters were still used to compensate for hand-held motion artifacts.

In vivo human studies were performed under a Duke University Medical Center (DUMC) Institutional Review Board-approved study with written informed consent in two healthy male subjects. Imaging was performed before, during and after saline injections. ECG-triggered image acquisition and motion filtering were utilized to minimize physiologic motion artifacts. Imaging and injections were performed by one of two experienced anesthesiologists (SAG and DBM).

III. RESULTS

Distal branches of the sciatic nerve in the popliteal fossa can be difficult to visualize, even in thin, healthy subjects, because of poor acoustic contrast in B-mode images. Figure 1 shows a comparison of *in vivo* B-mode and ARFI images of tibial and peroneal nerves in a 29-year old male subject being imaged with the VF10-5 linear array. The nerve contrast improvement is over 600% in the ARFI image compared with the B-mode image.

B-mode and ARFI images of the proximal sciatic nerve, in the upper third of the posterior thigh of a 29 year old male subject are shown in figure 2. Imaging was performed using the VF7-3 linear array. The sciatic nerve is shown in a longitudinal orientation. Notice that both the B-mode and ARFI image contrast are inverted compared with the nerves visualized in figure 1.

In addition to clear nerve visualization, anesthesiologists need to also be able to accurately localize their needles adjacent to these nerves. Figure 3 shows a needle adjacent to an *in situ* cadaveric sciatic nerve. Imaging was performed with the VF10-5 linear array. The ARFI image

has ~300% greater nerve contrast compared with the B-mode image. The needle was intentionally advanced to just pierce the nerve sheath (which is avoided clinically), as confirmed by a palpable 'pop' during insertion. This intentional nerve sheath piercing was performed to determine if this complication of regional anesthesia can be visualized to be avoided during clinical practice. There typically are not any indications on the B-mode image that the nerve has been perturbed when inadvertent intraneural injections occur. A purposeful injection of 3 cc of saline was performed on the same cadaveric sciatic nerve shown in figure 3 in a more proximal location, again after a palpable 'pop' was appreciated during insertion of the needle. The corresponding B-mode and ARFI images generated with the VF10-5 linear array post-injection are shown in figure 4, where fluid was injected in the left half of the nerve, allowing the right half to serve as a control. The needle was removed before the image was acquired. Notice the contrast reversal in the ARFI image where the fluid was injected.

The more superficial nerves in the brachial plexus are another common site for regional anesthesia procedures. The brachial plexus is in close proximity to the carotid artery, making ARFI imaging susceptible to more physiologic motion artifacts. Figure 5 shows *in vivo* B-mode and ARFI images of a brachial plexus during a saline injection in a 45-year old male subject using the VF10-5 linear array. ECG gating was used to minimize physiologic motion during data acquisition.

In addition to directly visualizing discrete nerves, either in cross section or a longitudinal view, anesthesiologists can target free nerve endings for regional anesthesia, as is typically done just superficial to the rectus sheath. The rectus sheath can sometimes be challenging to delineate from more superficial fascial planes, especially in overweight patients. ARFI imaging provides an opportunity to improve rectus sheath visualization since this fascial plane is much thicker and stronger than the more superficial planes, providing mechanical basis for improved image contrast. This is demonstrated in figure 6 using the VF10-5 linear array.

IV. DISCUSSION

The popularity of regional anesthesiology has grown considerably over the past few years with regular use of ultrasound guidance to identify nerve anatomy, critical adjacent structures (e.g., arteries), needle position and injection distribution. Ultrasound guidance is real-time and portable, allowing regional anesthesia procedures to easily be image-guided in pre-operative and operating room environments. B-mode imaging, however, has shortcomings when the acoustic contrast between nerves and adjacent structures is too small to provide adequate image contrast to visualize the relevant anatomy. This motivated exploring an ultrasound-based imaging technique that relies on tissue elasticity to provide an independent mechanism for improved image contrast.

Nerves consist of fibrous sheaths and neurons that are distinct from the other surrounding tissues, typically fat and skeletal muscle. The elasticity difference between these tissue types is responsible for the contrast in the ARFI images. As demonstrated in figures 1, 3 and 5, nerves can displace less than their surrounding tissues, which is indicative of them being stiffer; however, as demonstrated in figure 2, these same nerves can look more compliant (i.e., displace more) than their surrounding tissue when in a different anatomic location.

The tibial and common peroneal nerves (Fig. 1) in the popliteal fossa are typically surrounded by popliteal adipose tissue that isolates them from the connective insertions of the major muscles of the leg, including the medial and lateral heads of the gastrocnemius and the semimembranous, semitendinous and biceps femoris muscles of the hamstring. This adjacent adipose tissue is much more compliant than these nerves, allowing the ARFI image to display

these nerves with greatly improved contrast (>600%) compared with the concurrently acquired B-mode image.

Not all anatomic sites for regional anesthetic injection benefit from nerves being surrounded by significant adipose tissue. There are numerous locations along the brachial plexus that are targeted for upper limb blocks, including the interscalene approach shown in figure 5. Except in subjects with high body mass indices, the brachial plexus is more superficial than the nerves in the legs and is surrounded by skeletal muscles and fascia, both of which are stiffer than adipose tissue. These stiffer adjacent tissues are responsible for the reduced contrast in the ARFI images of the brachial plexus nerves compared with the nerves in the popliteal fossa, though the ARFI image contrast is still greater than that of the corresponding B-mode image contrast.

Nerves can appear relatively softer when the adjacent tissue is muscle, as demonstrated in figure 2. Figure 2 shows a more proximal location along the same nerves shown in figure 1, demonstrating how the ARFI image contrast is relative to the adjacent soft tissues, and absolute 'stiffer' or 'softer' distinctions cannot be used to delineate nerves in ARFI images. These relative stiffness differences are not restricted to different peripheral nerve locations in the same patient; relative stiffnesses are expected to vary at the same peripheral nerve locations between different patients in association with their body habitus. More obese patients will have greater fat content surrounding peripheral nerves that will affect the stiffness contrast with the targeted nerves.

The B-mode images in figure 5 demonstrate the challenge of tracking how nerves are displaced during anesthetic injections. In B-mode, the hypoechoic regions that are associated with the nerve roots can be distorted and coalesce with other hypoechoic regions in the surrounding structures as the fluid infuses the adjacent tissues. In the ARFI images, the nerve roots remain visible as discrete dark (i.e., stiffer) structures that translate and spread apart from one another as more fluid is injected. The B-mode and ARFI images were acquired simultaneously and are spatially registered, allowing useful procedural guidance information to be gleaned from both images concurrently.

One of the greatest utilities of ultrasonic image guidance of regional anesthesia procedures is repositioning needles to avoid injections into critical structures, including the nerve itself. While Doppler imaging can be used to confirm the presence of blood vessels, nerves cannot be highlighted in a similar manner in B-mode images to insure proper injection placement. The ideal injection bathes the nerve with anesthetic; injections into the nerve itself can have significant adverse side effects, including infection and nerve paralysis. The intentional injection of the cadaveric sciatic nerve in figure 3 demonstrates how the concurrent visualization of the needle and the nerve can have great utility in helping prevent inadvertent intraneural injections. In figure 3, the nerve is more clearly delineated in the ARFI image, and the needle that was introduced through the upper left quadrant of the image can be seen piercing the nerve sheath. The breach of the nerve sheath by the needle is more apparent in the ARFI image than the associated B-mode image. While the piercing of the nerve sheath with a needle can be accompanied by a 'pop' that can be felt by the anesthesiologist, such sensations are not always detected and can be less obvious in smaller nerves with thinner fibrous nerve sheaths. Therefore, having images that can confirm proper needle placement should reduce the occurrence of these adverse side effects. It would also be advantageous to a clinician to have feedback on an image when an inadvertent intraneural injection has occurred, but this is not readily apparent in many B-mode images. Figure 4 shows how the injected region of nerve can experience a contrast reversal in the ARFI image that could be used to highlight regions that have been compromised by the procedure.

The identification of anatomic landmarks beyond discrete nerves is also of great utility in regional anesthesia procedures. one such application is the rectus sheath block, as shown in figure 6, where fascial planes need to be distinguished from one another. Injection of anesthetic in a superficial plane will lead to an inadequate block while puncture of the rectus sheath to target a more distal structure will lead to breach of the peritoneal space, causing potential infection, hemorrhage and injury to abdominal viscera. In figure 6, the rectus sheath is seen as being considerably thicker and relatively stiffer than the more superficial fascial planes, providing a confirmation of the proper plane for anesthetic injection, similar to how Doppler is used to confirm blood vessel identification.

ARFI imaging utilizes short duration (<1 ms), high intensity (*in situ* $I_{sppa} \sim 1500$ W/cm²) insonifications to generate enough radiation force to appreciably displace tissue. These insonifications have been evaluated for their thermal safety for past clinical applications of ARFI imaging and the associated heating ranges from 0.2–2 °C, depending on the excitation frequency and specific beam sequences.^{24–26} The introduction of needles into the ROE creates a reflecting boundary that can increase the local heating proximal to this interface; however, the reflecting surface area of these needles is small compared to other reflecting interfaces in the body, such as bone, that appreciably affect ultrasonic heating patterns.²⁷ Thermal simulation and thermocouple measurement studies are necessary to quantify the changes in tissue heating associated with the presence of needles in the ROE. Another safety consideration associated with ARFI imaging of regional anesthesia procedures involves the risk of cavitating air bubbles that may be introduced during the injection of the local anesthetic. This risk is reduced by using higher-frequency radiation-force excitations and avoiding the introduction of bubbles during the injections.²⁸ Both heating and cavitation must be considered when designed radiation-force-based excitations for ARFI imaging during regional anesthesia procedures.

V. CONCLUSIONS

ARFI images can provide improved contrast over B-mode images that are currently used to guide regional anesthesia procedures. Peripheral nerves are typically surrounded by different tissue types that can provide a mechanical basis for improved elasticity-based image contrast when acoustic contrast is limited. Nerves surrounded by fat typically displace less and are relatively stiffer than their adjacent tissues while these same nerves can appear more compliant when surrounded by large volumes of skeletal muscle. Contrast improvements of up to 600% were possible in large distal lower limb nerves but more comprehensive studies are needed to establish the improvements in nerve visualization at a variety of nerve imaging locations. It is also feasible to use ARFI images to visualize the distortion of nerve roots during injections, allowing anesthesiologists the opportunity to reposition needles for the remaining infusion of anesthetic. Needle proximity to target nerves can also be evaluated in ARFI images, providing the opportunity for optimizing injection placement while reducing the likelihood of inadvertent intraneural injections. This work has demonstrated the feasibility for B-mode and ARFI images to be used concurrently to improve regional anesthesia procedure guidance for greater efficacy and reduced adverse side effects.

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FIG. 1.

In vivo B-mode (left) and ARFI (right) images of the tibial and common peroneal nerves in a 29-year old subject, just distal to their bifurcation from the sciatic nerve in the popliteal fossa. The ARFI image was generated using two excitation focal zones at 15 and 20 mm with the VF10-5 linear array. The peak displacement in the ARFI image is 4 μm . ECG data acquisition gating was not used in generating the ARFI image. Notice that the two nerves are clearly delineated as stiffer (darker) circular structures in cross-section; their location is not readily apparent in the B-mode image (they have been outlined in yellow (tibial) and green (popliteal) based on the ARFI image boundaries). The improvement in nerve contrast is over 600% in the ARFI image compared with the B-mode image.

FIG. 2.

In vivo B-mode (left) and ARFI (right) images of the same sciatic nerve shown in figure 1, but in a more proximal location in the upper third of the thigh, imaged longitudinally from a posterior approach using a VF7-3 linear array. Green arrows have been used to highlight the nerve location in both the B-mode and ARFI images; the arrows are in identical positions in both images.

FIG. 3.

In situ distal cadaveric sciatic nerve with an 18 gauge needle intentionally piercing the upper left quadrant of the nerve sheath, imaged using the VF10-5 linear array. There is significant decorrelation deep to the needle due to poor SNR but the tip of the needle and the edge of that decorrelation can be seen inside the left border of the sciatic nerve, which appears dark (stiff) in the ARFI image. The nerve contrast improvement is ~300% in the ARFI image compared with the B-mode image.

FIG. 4.

In situ cadaveric sciatic nerve after an intentional intraneural injection with 3 cc of saline in the left half of the nerve imaged using the VF10-5 linear array. The location of the nerve has been circled in the B-mode image using some circumferential landmarks from the corresponding ARFI image. The needle was removed before the image was acquired. Notice the ARFI image contrast reversal in the left half of the nerve that has been infused with saline compared with the right half of the nerve that was not injected.

FIG. 5.

B-mode and ARFI images of the brachial plexus *in vivo* from an interscalene approach pre-injection (top row), after a 2 cc saline injection (middle row) and after an additional 4 cc saline injection, for a total of 6 cc saline injected into that site (bottom row). Imaging was performed using the VF10-5 linear array. Pre-injection, the needle (yellow arrows) was placed adjacent to the lower left aspect of the nerve bundle (green arrows). Notice that the substructures of the nerve bundle spread apart and are displaced to the right after the saline injections. Some of the nerve substructures translated over 5 mm laterally in response to the injection. This translation is more apparent in the ARFI images than the corresponding B-mode images.

FIG. 6.

In vivo B-mode and ARFI images of the rectus abdominus muscles and rectus sheath in a 29-year old subject. The posterior sheath is located at a depth of 14–16 mm in these images; the anterior surface is the target for local anesthetic injection. The ARFI image highlights the greater mechanical contrast that exists in this targeted layer compared with the more superficial fascial planes (i.e., it is darker, representing greater relative stiffness compared to the adjacent muscle and superficial fascia).

TABLE I

Radiation force excitation and displacement tracking configurations for the VF7-3 and VF10-5 linear arrays.

	VF7-3 excitation	VF7-3 tracking	VF10-5 excitation	VF10-5 tracking
Transmit focal depth (mm)	10–25	<30	5–20	<20
Receive focal depth (mm)		dynamic		dynamic
Transmit F/#	2.0	2.0	1.5	2.0
Receive F/#		0.5		0.5
Frequency (MHz)	3.3	7.3	6.7	10.0
Elevation focus (mm)	~37	~37	~19	~19
Lateral line spacing (mm)		0.18		0.15
PRF of track lines (kHz)		9.1		9.1
Excitation duration (μs)	60–90		23–30	