Group 03: Photoacoustic System for Spinal Surgery

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Introduction

I investigated using a photoacoustic system to track three different drill tip models as they passed through a pre-drilled human vertebra, as well as the visualization of blood through bone. The photoacoustic tracking coordinates were registered to both ultrasound and CT images of the vertebra. This system has clinical significance in spinal surgeries, particularly when inserting pedicle screws during spinal fusion surgery.

Almost half a million spinal fusion surgeries are done in the US annually, and the number of surgeries is increasing rapidly [1]. Intraoperative radiographs remain essential to successfully performing these surgeries [2], although these expose surgeons and patients to harmful radiation. Ideally, the surgeons should be able to visualize the spine in real-time without themselves and the patient being exposed to radiation. Ultrasound (US) imaging is safe and affordable in the operating room, but there are limitations. It can be used to place epidurals [3], but US images of bone are distorted, and it can be difficult to image important anatomical landmarks. Previous work has shown that a safe drilling location can be found based on the signal in a photoacoustic image [4].

Methods

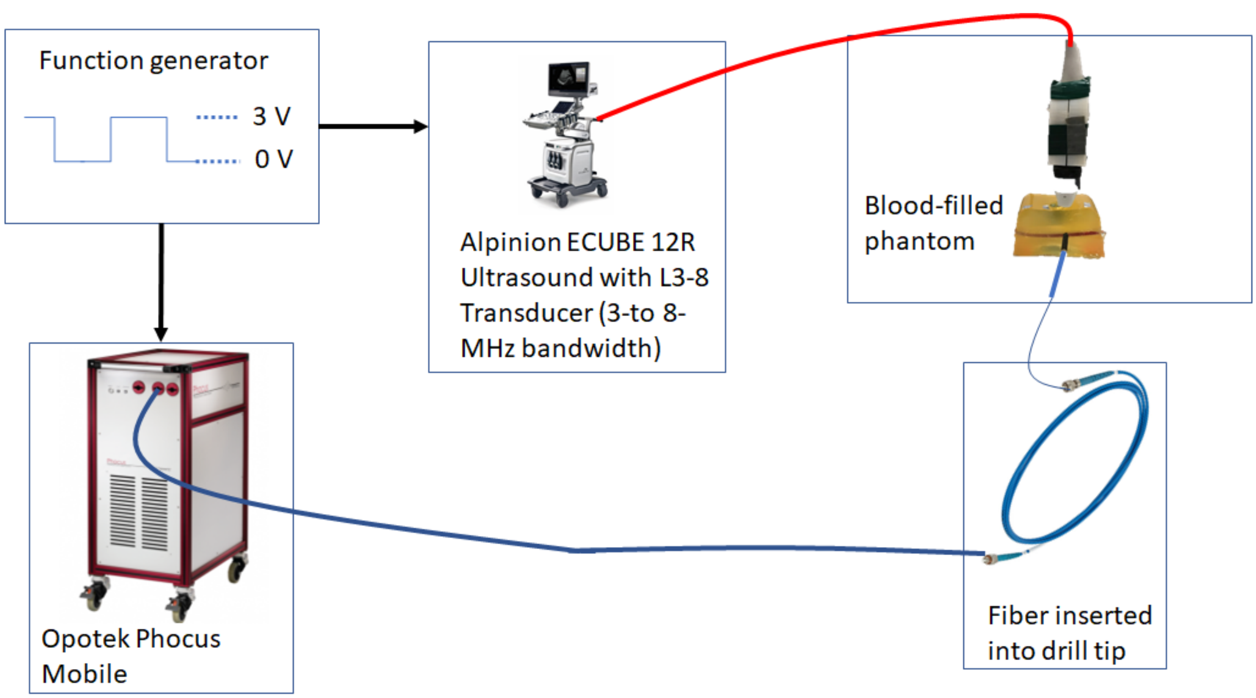

Figure 1. Experimental design for blood visualization.

Both experimental systems shared the same basic connections. An oscilloscope generates waveforms that are synced to the laser's Q-switch and sent to the ultrasound system. In this way, image collection is coupled with the generation of a photoacoustic signal from the pulsed laser. The laser is coupled to the drill tip via an optical fiber, which all together creates the drill prototype. The drill prototype is used on the human bone and blood in the phantom to generate relevant surgical data. The ultrasound transducer is held against the phantom to collect the raw data. Finally, this is sent back to the ultrasound system which generates a live display of the system. The OPO crystal was tuned to 760 nm for all experiments to ensure tracking data could be applied to the visualization of blood. The wavelength was chosen because it is in the peak absorption range of deoxygenated blood, making it optimal for photoacoustic imaging of blood. A linear transducer was used to image the blood-filled phantom, but a phased array was used to image the drill tips entering the vertebra.

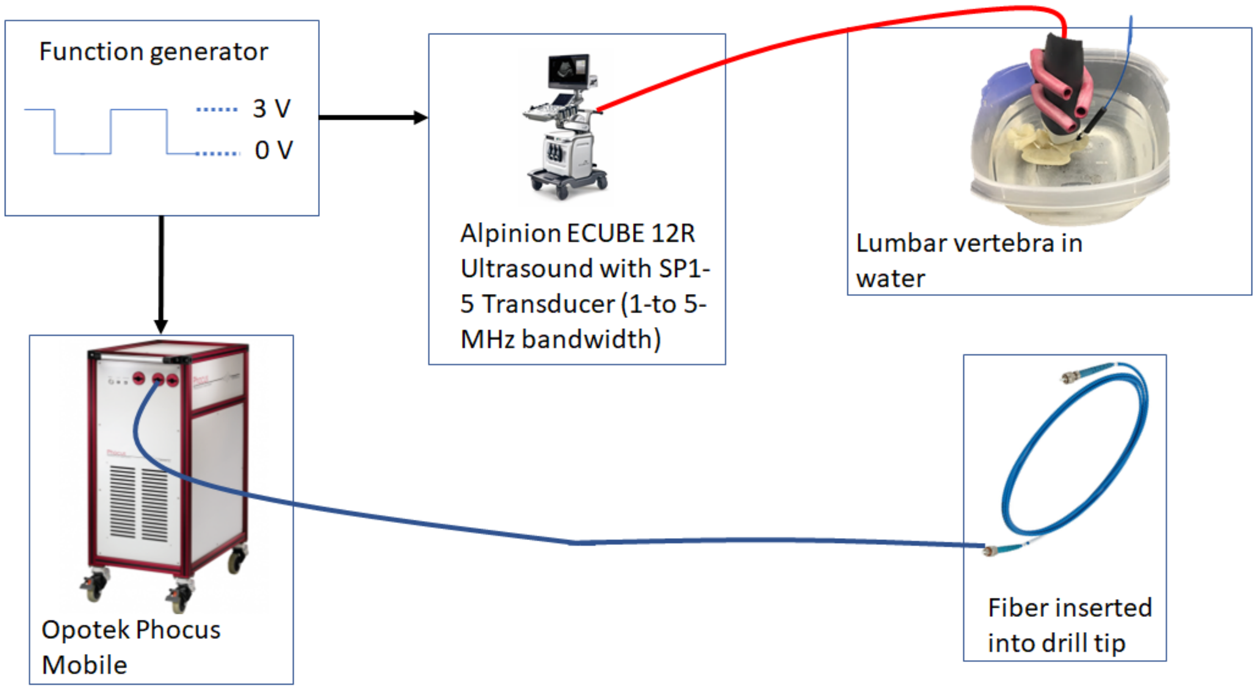

Figure 2. Experimental design for tracking experiments.

Channel data was collected and processed using pre-existing beamforming scripts in MATLAB. For the drill tracking experiments, the peak PA signal amplitude was found for each PA image collected. These points were plotted on a matched US image and registered to CT coordinates.

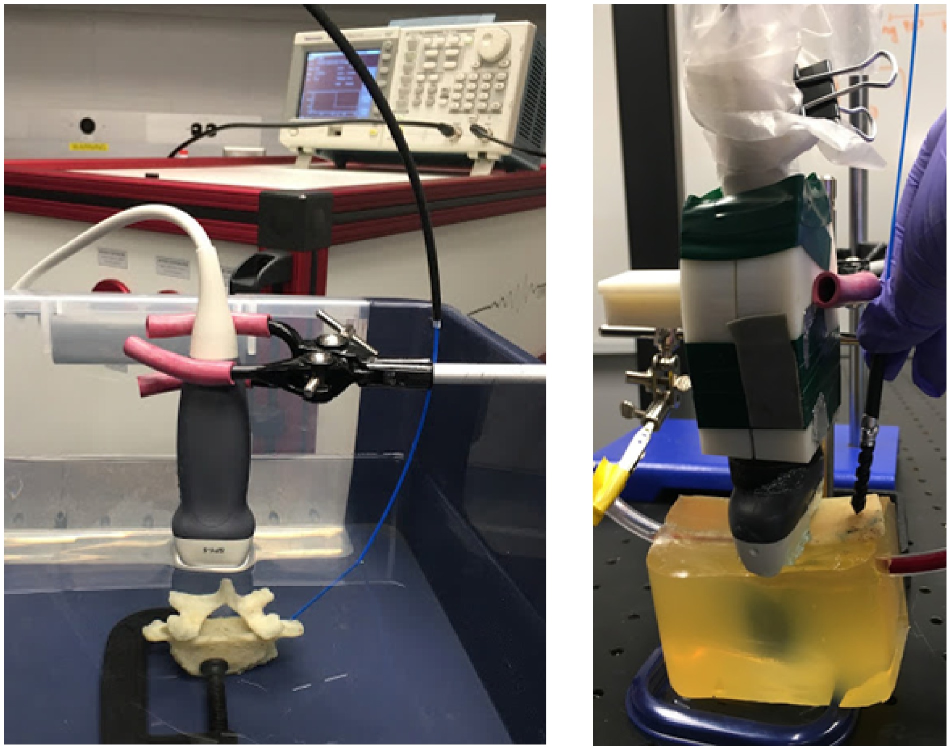

Figure 3. *Left:* phased array set-up for drill tracking experiments; *Right:* linear array set-up for blood visualization

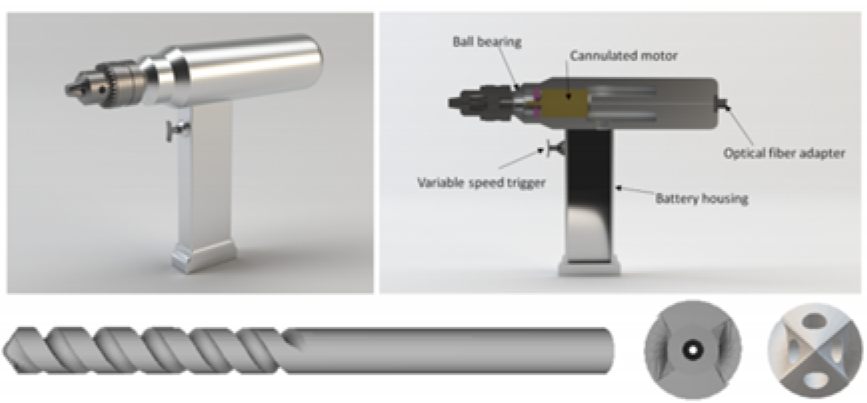

Figure 4. The proposed drill prototype and three drill tips used. From left to right: solid tip, single-holed tip, multiple-holed tip

Results

Using the proposed PA system, blood was not easily visualized through bone. However, the change in signal for different bone thicknesses is evident. There was more diffraction present in the thicker bone. In the images shown below, a bare fiber is held in approximately the same position as the vessel in the phantom. The PA signal shown does not correspond to the anatomy, just to the presence of the fiber emitting pulsed light.

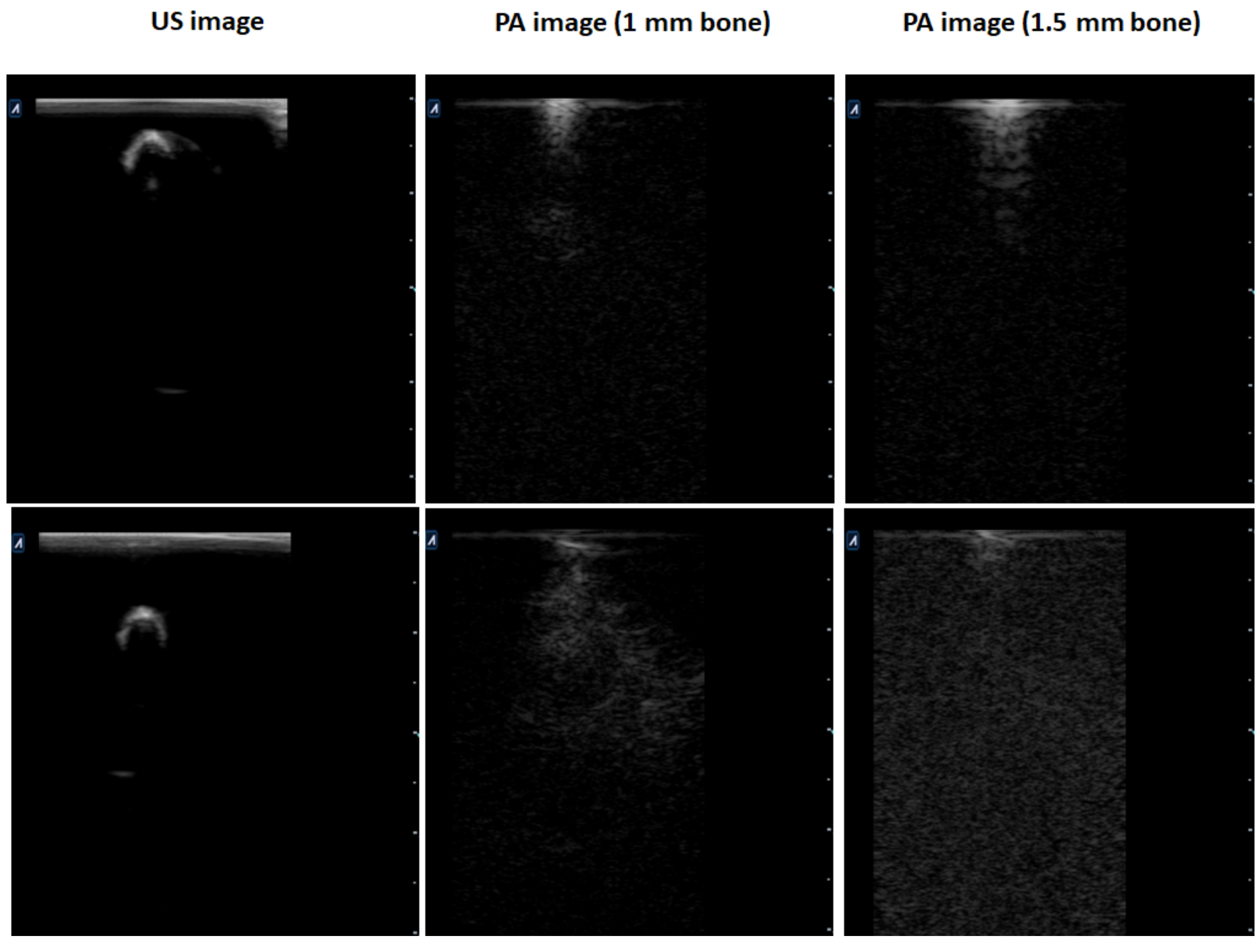

Figure 5. Results from blood visualization experiments. *Top:* blood vessel 5 mm deep; *Bottom:* blood vessel 10 mm deep

Tracking data was collected using a phased array. For each trial, a US image was taken in the same position as the PA tracking data for that trial. The highest amplitude was plotted as the drill tip was inserted into the vertebra. Tracking the drill tip was fairly successful, though registration was imperfect. As seen below, the tracked signal does not appear to enter the bone in the matched CT image. Noisy data also caused significant outliers along the bounds of the phased array capture. Based on these trials, the single-holed drill tip produced the smoothest (most precise) tracking.

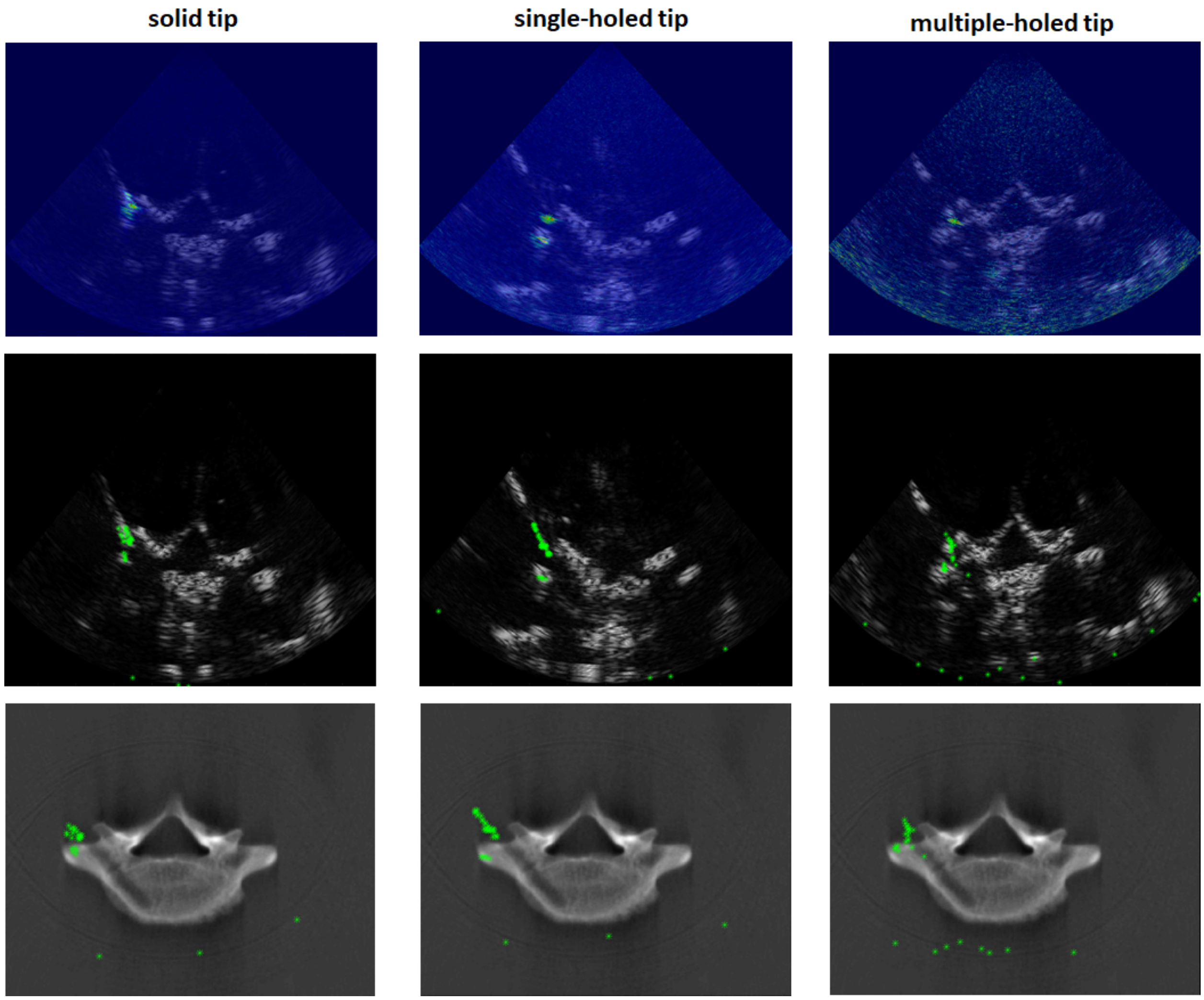

Figure 6. *Top row:* representative PA image overlaid on US image; *Middle row:* tracking results on US image; *Bottom row:* coordinates overlaid on CT registered image.

I was given the bonus goal of investigating how the angle of the fiber affects the PA image. For this data I registered the PA heatmap to a US image taken with the vertebra held in the same position. Video data was also collected using an iPhone 6s to determine the angle of the fiber during the data sequence. As the fiber is rotated from a vertical position to a more horizontal one, the PA signal has different properties. The signal appears strongest in an intermediate position and weakest in the edge cases. This is consistent with past work showing a brighter PA signal corresponds to the location of the pedicles, and can be used to determine where it is safe to drill. A “good” fiber position is defined as being centered in the trajectory of the pedicle with no chance of breaching the bone. A “bad” fiber position is defined as the opposite: it is likely the bone would be breached in this orientation.

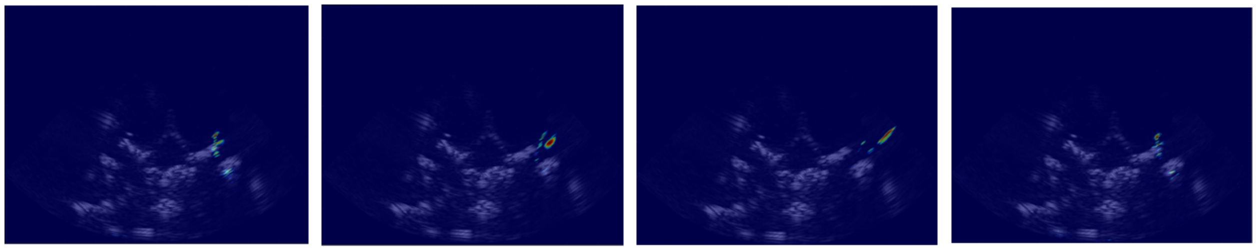

Figure 7. PA images overlaid on a US image as the fiber is rotated. From left to right the fiber is moving from a more vertical orientation to a more horizontal orientation.

Management Summary

I planned and carried out all of the experiments, with the advice of Dr. Bell when necessary. I met with her every Friday to discuss progress and determine whether any plans should change. The beamforming scripts were given to me by graduate students Michelle Graham and Eduardo Gonzalez and edited or augmented as necessary. The CT registration code and CT data I used were also given to me by Eduardo Gonzalez. I wrote my own scripts for pipeline processing, as well as transforming and plotting points. These are included in the technical appendix.

Originally, visualizing blood through bone was a minimum deliverable, and I ended up being unable to successfully demonstrate that vessel boundaries can be found with this system. Acquiring fresh blood samples for data collection combined with problems imaging with the OPO laser slowed progress with these experiments. I lost a couple weeks when the system malfunctioned before Spring Break. To make up for lost time, I began working on my tracking deliverable early because these experiments were more simple to set-up. I was able to achieve the tracking that I wanted, but had some problems when registering the PA coordinates to the CT images of the vertebra. I did not have time to work on novel image processing methods, my maximum deliverable. However, I did investigate the difference in PA signal when the optical fiber is held at different angles with respect to the pedicle, which was not an original goal.

In the future, this system can be optimized for visualizing blood while maintaining its ability to track the drill tips through bone. Looking back, I should have optimized the system for imaging blood through bone early enough to order a new fiber or 3D print different drill tips with different specifications. There is also an opportunity to optimize this or other PA systems for visualizing nerves and the spinal cord at a different wavelength. The tracking accuracy and smoothness can be improved by introducing more image processing methods and filtering out noisy data.

Technical Appendices

Beamforms PA data.

- Blackberrie Eddins

```
clear all;
close all;

file = 'D:/5-8/PAsolid';
info = dir([file '/*RF.mat']); % get ch data filenames

for i = 1:length(info)
    delay_data = delay_PA_phased([file '/' info(i).name], [file '/
Sequence.mat']);
    bmf_data = beamformer_DAS_PA_phased(delay_data, 1000, 60);
    save(['bmf_data_' 'solid2CT' '_' num2str(i)],'bmf_data')
    i
end
% save(['bmf_data_' file],'bmf_data')
```

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Overlays PA data onto matching US data. Also finds and plots PA signal peaks.

- Blackberrie Eddins

```
US = load('bmf_data_USsolid.mat');

points = zeros(31,2);
store = [];
for i = 1:31
    PA = load(['bmf_data_PA_solid_' num2str(i) '.mat']);
    bright = max(PA.bmf_data.bmf_img(:));

    % US plot
    hf = figure;
    h1 = axes; colormap(h1,'gray');
    p1 = imagesc(US.bmf_data.bmf_img);

    % PA plot
    h2 = axes; colormap(h2, 'jet');
    p2 = imagesc(db(PA.bmf_data.bmf_img./bright),'alphadata',0.5,[-15
 0]);
    set(h2, 'color', 'none', 'visible', 'off');
    linkaxes([h1 h2])
    hold on,

    [r c] = find(PA.bmf_data.bmf_img == bright);
    points(i,:) = [c r];
    plot(c, r, 'Marker','*','Color', 'g', 'MarkerSize',
 10),%title('Normalized DB PA Image')
    saveas(hf,['solid' '_plot_' num2str(i)],'png')

end
save('solid_points.mat','points')

hf = figure;
imagesc(US.bmf_data.bmf_img), colorbar, colormap gray,
hold on
plot(points(:,1), points(:,2),'g*')
saveas(hf,'solid_US_plot','png')
```

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Tranforms tracking coordinates to CT space and plots them on CT image.

- Blackberrie Eddins

```
load('fixed_CT.mat')
load('sh2CT_points.mat')
load('shtform.mat')
load('bmf_data_US2CTsh.mat')

tpoints = transformPointsForward(tform,points);
hf = figure; axis image,
imagesc(fixed_CT),colormap gray, hold on
plot(tpoints(:,1),
 tpoints(:,2), 'Marker','*','LineStyle','none','Color', 'g', 'MarkerSize',
 8)

saveas(hf,'sh_CT_plot_','png')
```

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<u>Citations</u>

1. Rajaee SS, Bae HW, Kanim LE, Delamarter RB. Spinal fusion in the United States: analysis of trends from 1998 to 2008. Spine (Phila Pa 1976). 2012 Jan 1;37(1):67-76. doi: 10.1097/BRS.0b013e31820cccfb. PubMed PMID: 21311399.
2. Vidal C, Ilharreborde B, Queinnec S, Mazda K (2016) Role of intraoperative radiographs in the surgical treatment of adolescent idiopathic scoliosis. J Pediatric Orthop 36(2):178–186
3. Chen, Carl P. C. M.D. et al. Ultrasound Guidance in Caudal Epidural Needle Placement. Anesthesiology. **101**(**1**):181-184, July 2004.
4. Shubert J, Bell MAL, A novel drill design for photoacoustic guided surgeries 2018