Photoacoustic-based Approach to Surgical Guidance Performed with and without a Da Vinci Robot

Introduction

The main goal of this paper was to assess and quantify safety zones using a photoacoustic imaging system. Safety zones were defined based on the distance between blood vessel boundaries. Experiments were done using the da Vinci Surgical System to show that photoacoustic imaging was relevant to minimally invasive surgeries, specifically those that are teleoperated. The authors achieved sub-millimeter accuracy in both amplitude-based and coherence-based beamforming, and in the presence of bovine tissue up to 4.5 mm. Based on these results, photoacoustic image-based measurements of anatomy can be used in real-time surgical path-planning.

Background

This paper proposes photoacoustic image-guided surgery to visualize nerves and blood vessels intraoperatively in order to reduce the risk of damage to these delicate structures. The specific surgeries it lists are mastoidectomies (the removal of mastoid air cells) and endonasal transphenoidal surgeries (for example the removal of a pituitary tumor through the nasal cavity). During mastoidectomies, there is a risk of rupturing the facial nerve which can cause twitching, weakness, or paralysis of the face. There is a risk of damaging the carotid arteries behind the sphenoid bone during endonasal transphenoidal surgeries. Surgery to correct carotid artery injury has 14% morbidity, and carotid artery injury has 24-40% mortality rates. In addition to the applications in otorhinolaryngology, the paper investigates visualization of the uterine blood supply during a laparoscopic or transvaginal procedure.
The current standard of care is to take pre-operative images to plan these surgeries, but the locations of these delicate structures during surgery can significantly differ from the static images. Some real-time methods exist with MRI and CT, but CT introduces radiation, and MRI is very expensive with a lower spatial resolution. For laparoscopies and transvaginal procedures ultrasound imaging and endoscopes can be used to visualize most anatomy, but may not have the same visualization of the blood vessels as in a photoacoustic image.

Photoacoustic imaging works by inducing an acoustic signal in a target structure. The target absorbs light transmitted by a pulsed laser, which causes thermal expansion. More importantly, thermal expansion leads to the generation of an acoustic signal. Different anatomical features, especially blood and nerves, have been shown to have peak absorption at different wavelengths, allowing photoacoustic systems to be optimized for different applications.

Experiments and Results

Technical Approach

They used a function generator to synchronize the ultrasound transducer with the laser's q-switch (pulse timing). They used three different lasers throughout their experiments. First they used a laser diode which required a separate power supply and a collimator to minimize the energy lost on fiber entry. The laser diode had a wavelength of 905 n In addition, they used anm. Ultra100 Nd:YAG laser focused through an aspheric lens. The Ultra100 Nd:YAG laser had a 1064 nm wavelength. They also used a Phocus mobile laser at the 1064 nm wavelength. In experiments the carotid arteries were modelled with dark rubber tubing and placed inside a phantom made of plastic and filled with water. The uterine wall was modelled with a 3D-printed representation of the uterine vessels, and ex vivo bovine tissue was draped over the structure with thickness varying from 1-4.5 mm. To collect photoacoustic images, the optical fiber was held either manually or with the da Vinci arm. With a single-fiber system, only one artery can be visualized at a single point in time. If held manually, the fiber was swept horizontally across the target structures to compose a compounded image in post-processing.

When using the da Vinci system, the researcher sat at the console to control the robotic arms which could hold various tools. One manipulator was given a surgical tool with a fiber attached and the other held the ultrasound probe. The tool tip could be positioned using data from the endoscope and the photoacoustic images. The da Vinci's kinematic data was used to estimate the vessel position, but photoacoustic image processing was also used. To create the compounded image, the fiber was translated horizontally in an arc instead of through a straight path like in the manual approach.

During experiments, they held the ultrasound probe approximately orthogonal to the vessels as well as approximately parallel. While they did not do significant analysis on the difference between these two methods, they did include representative images showing that both were adequate ways to visualize the anatomy.

Error Analysis

They used two methods to measure the distance between vessels, one with da vinci kinematics, and one with the image data. Photoacoustic image data distances were found by finding the brightest pixels and then measuring the distance between them. The three-dimensional distance formula was used to estimate vessel distances from the da Vinci kinematic data. These distances were compared to the ground truth, which was measured using calipers. In this comparison, they found the root mean square (left) and mean absolute errors (right), with equations shown below.

$$\text{RMS error} = \sqrt{\frac{\sum_{n=1}^{\text{NVS}}\left(\sum_{m=1}^{\text{NVT}_n} D^2\right)}{\text{TNVT}}} \qquad \text{MAE} = \frac{\sum_{n=1}^{\text{NVS}}\left(\sum_{m=1}^{\text{NVT}_n} |D|\right)}{\text{TNVT}}.$$

The uterine vessel model was covered with bovine tissue and three distances between the modelled vessels were measured under varying tissue thicknesses. There was no specific trend as tissue thickness increased, however, they concluded that at each tissue thickness they could find at least one vessel with submillimeter accuracy.

There was no significant difference between results obtained with the two 1064 nm lasers. Both the delay and sum (DAS) and short lag spatial coherence (SLSC) beamforming methods had submillimeter accuracy, but the DAS method was slightly more accurate because the image post-processing was amplitude based. The SLSC method produced images with higher contrast, but the brightest pixels weren't as dependent on vessel location. The da Vinci tracking data had a significantly higher error of a couple millimeters. Trials in which the fiber was held manually were also more accurate than those held teleoperatively.

Assessment

The key results were listed by the authors as: obtaining the accuracy of hand-held image-based vessel separation measurements, differentiating between the accuracy of manual and teleoperated control of an optical fiber, similar results despite discrepancies between experimental procedures used (specifically laser beamforming methods and fiber control), and finally variations between different ultrasound probe orientations and tissue thicknesses. Realistically, the authors were most successful in achieving the accuracy measurements, which were extremely detailed. The paper did not do any quantitative analysis on the different ultrasound probe orientations, which could have been interesting. There was quantitative analysis for the tissue thickness trials, although the data did not seem to have a pattern, and they did not sufficiently explain or propose theories as to why they obtained the results they did.

Overall, the paper provided a detailed background of the clinical importance of their project as well as a detailed description of their technical approach, which makes their experiments easily reproducible. Their experiments showed the versatility of their photoacoustic system across different lasers, beamforming methods, and ultrasound probe orientations, which further shows the benefits of such a system to plan surgical paths. On the contrary, they did not use any real blood in experiments. Blood has different acoustic properties than rubber, and could reduce the versatility of their experiments. They also used a simple pixel intensity based algorithm for post processing. A more robust algorithm could have higher accuracy in SLSC and other high contrast beamforming methods, which would eliminate the need for the image quality, processing accuracy trade-off. In their experiments the tool was not visualized with the photoacoustic system, and instead the user had to use the da Vinci endoscope to position the tool. Although the imaging systems were nicely integrated, it would be easier for the surgeon to only look at one screen instead of two while operating.

Future Work

This system can be further optimized for teleoperation. As stated previously, integrating the visual field would increase the clinical viability. Path planning can also be taken further by creating virtual fixtures or choosing a path for the surgeon to follow. Introducing real blood into the experiments would be an important step towards proving the system could work in a living environment. The system can also be optimized for different structures (like nerves) at different wavelengths. Future image processing techniques include comparing algorithms that aren't amplitude based to improve SLSC and other high contrast beamforming methods' imaging accuracy.

Conclusions

This paper shows that there is no definitive trend in the magnitude of error as vessel separation increases. Consistency is important for applying this method to a large range of anatomy. Distances computed from photoacoustic data are significantly more precise than those found from da Vinci tracking kinematics, showing that the extra time and processing is needed in path planning. The authors have shown that a photoacoustic tracking system only has submillimeter error, which can widen the surgical field in minimally invasive surgeries. Finally, this paper shows SLSC beamforming is better for vessel visualization, but DAS is better for analysis (based on signal amplitude).

Citation

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