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Research Article

Localization of Transcranial Targets for Photoacoustic-Guided Endonasal Surgeries

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ABSTRACT

Neurosurgeries to remove pituitary tumors using the endonasal, transsphenoidal approach often incur the risk of patient death caused by injury to the carotid arteries hidden by surrounding sphenoid bone. To avoid this risk, we propose intraoperative photoacoustic vessel visualization with an optical fiber attached to the surgical tool and an external ultrasound transducer placed on the temple. Vessel detection accuracy is limited by acoustic propagation properties, which were investigated with k-Wave simulations. In a two-layer model of temporal bone (3200 m/s sound speed, 1-4 mm thickness) and surrounding tissues, the localization error was $\leq$2 mm in the tranducer's axial dimension, while temporal bone curvature further degraded target localization. Phantom experiments revealed that multiple image targets (e.g. sphenoid bone and vessels) can be visualized, particularly with coherence-based beamforming, to determine tool-to-vessel proximity despite expected localization errors. In addition, the potential flexibility of the fiber position relative to the transducer and vessel was elucidated.

1. Introduction

Pituitary tumors cause a variety of hormonal complications, compressing critical nerves and arteries at the base of the brain, and creating a potential for vision loss. Endonasal, transsphenoidal surgery is the most common method for removal of pituitary tumors to reverse endocrine problems and restore normal hormone balance [1]. In this minimally-invasive procedure, an endoscope is used to visualize the surgical field and tools such as a drill for sphenoidal bone removal and a curette for tumor resection are passed through the nostrils and nasal septum to access the sphenoid sinus and resect the tumor, as depicted in Figure 1(a). However, the endoscope is limited to visualizing superficial structures. One of the most significant surgical complications arises from accidental injury to the carotid arteries, located within 1-7 mm on either side of the pituitary gland and hidden by the sphenoid bone [2,3], as illustrated in Fig. 1(b). Accidental injury to these arteries creates a serious surgical setback, resulting in extreme blood loss, thrombosis, neurological deficits, stroke, or possibly death, with 14% morbidity and 24-40% mortality rates [4,5]. It may be treated with emergency interventions, albeit with a high risk of irreversible neurological damage [6].

This complication occurs most frequently with novice surgeons who have performed fewer than 200-500 of these surgeries and thus are not sufficiently familiar with potential variations in the anatomy surrounding the pituitary gland [7,8]. In addition, this procedure is particularly challenging in pediatric patients who are born with small nasal cavities that mainly develop into their full size after puberty [9,10]. Approximately 75% of hospitals in the United States treat 2-25 cases annually [11], thus, there are generally limited opportunities for novice surgeons to gain necessary caseload experience.

Although intraoperative x-ray or CT may be used to navigate the bony anatomy surrounding a pituitary tumor [12], it does a poor job of visualizing blood vessels and incurs the risks associated with radiation exposure. Intraoperative magnetic resonance (MR) imaging is another option, but it is costly, and generally suffers from low resolution and poor image quality due to the weak magnetic field [13]. MR aniography is a similarly expensive option with poor vessel resolution, and it is not suitable for patients with pacemakers or metal implants [14]. In MR and CT angiography, it is additionally burdensome to synchronize the injection of contrast agents with intraoperative imaging. In addition, none of these options support continuous, real-time, intraoperative vessel visualization.

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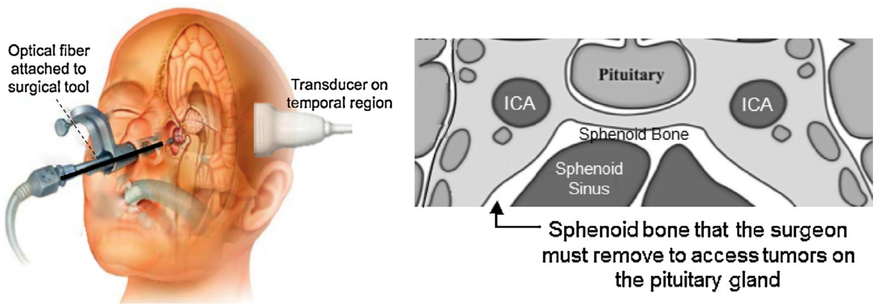

(a) (b)

Fig. 1. (a) Photoacoustic system concept. (b) Coronal view of the anatomy surrounding the sphenoid bone (adapted from [22]). To visualize the internal carotid artery (ICA) intraoperatively with photoacoustic imaging, light must pass through the sphenoid bone.

While transcranial ultrasound provides real-time imaging, it requires low transmit frequencies for skull penetration, which translates to poor spatial resolution and necessitates expert sonographers to interpret images [15]. A real-time Doppler ultrasound probe was developed to assist surgeons with detecting carotid arteries [16], but failure was reported due to the incorrect interpretation of images and Doppler signals, resulting in misjudgment of the carotid artery location [3].

Real-time photoacoustic imaging [17–19] is a faster, safer, less expensive option (compared to CT and MR imaging), implemented by emitting nanosecond light pulses from a laser [20]. When the laser irradiates a target, such as bone or vessels, the target absorbs the light, according to its optical absorption spectrum. Optical absorption causes thermoelastic expansion and generates acoustic waves that are detectable with an ultrasound transducer. Signal detection with photoacoustic imaging is expected to be advantageous over conventional ultrasound imaging because there is less acoustic interaction with the skull. The acoustic waves are only required to pass through the skull once, rather than twice as in pulse-echo ultrasound and as a result, the waves are less susceptible to the sound scattering and aberrations that occur when they encounter the skull. In addition, higher frequency probes (compared to the standard low-frequency transcranial ultrasound probes) may be used to obtain better resolution [21].

We propose to adapt photoacoustic imaging for this task [21] by placing a transducer on the temple of the patient's skull, as shown in Fig. 1(a). The temporal region includes the pterion bone which is the thinnest portion of the human skull measuring 1-4.4 mm thick [23]. An optical fiber, coupled to a laser, would be attached to a surgical tool. During surgery, the tool and fiber will be inserted into the nasal passage where the optical fiber would illuminate the sphenoid bone which has a thickness of 0.4-8.8 mm [24,25]. Intraoperative photoacoustic images will be acquired to visualize blood vessels and sphenoidal bone.

The ability to visualize the distance between sphenoid bone (which could act as a surrogate for the tool tip position) and blood in the photoacoustic images would inform surgeons of their proximity to the carotid artery as the sphenoid bone is being removed. Alternatively, a metal tool tip could possibly be visualized in the photoacoustic image if the attached fiber additionally illuminates it and generates a photoacoustic response from the metal tip [26] that is acoustically coupled to the surrounding cranial environment. In addition, for more accurate navigation and tool-to-vessel orientation, photoacoustic images could be registered with the preoperative CT or MR images that are currently used to guide surgical procedures. Although transcranial photoacoustic imaging was previously demonstrated with neonatal and adult skulls [27–29], the proposed embodiment of this approach is novel.

Potential challenges include uncertainty surrounding target locations (due to acoustic heterogeneities within the skull) and varied image quality with fiber placement (given the flexible separation of light delivery from acoustic reception). Thus, the goals of this paper are to quantify the expected target shift as functions of temporal bone thickness and speed of sound, devise methods to compensate for this target shift, and characterize target visualization as a function of fiber placement. Challenges with acoustic propagation through the temporal bone are investigated with theoretical equations and k-Wave [30] simulations, because it is difficult to experimentally decouple bone thickness and sound speed. However, challenges with target visibility and optical propagation through the sphenoid bone are investigated with phantom experiments. Although these multiple challenges are investigated independently to understand their individual influences, we expect them to coexist during surgery.

2. Methods

2.1. k-Wave Simulations

A k-Wave simulation [30] was designed to explore the effect of temporal bone thickness and speed of sound on the location of targets in reconstructed photoacoustic images. The simulated phantom consisted of a temporal bone layer at the face of the probe and a horizontal, linear photoacoustic target, which could represent the sphenoid bone or a blood vessel. The temporal bone was modeled with a density of 1900 kg/m^3 [31]. The target and surrounding medium were modeled with a sound speed of 1540 m/s and a density of 1000 kg/m^3.

To investigate the expected variations due to speed of sound and thickness independently, the temporal bone thickness was varied from 1-12 mm (in 1 mm increments) with its sound speed fixed to 3200 m/s [32–34]. Similarly, the speed of sound in the temporal bone was varied from 2000 to 4000 m/s [33] (in 200 m/s increments) with thickness fixed to 7 mm. Note that negligible changes were observed when the density was varied (1000-2200 kg/m^3) with sound speed and thickness fixed. A total of five arbitrary target depths were investigated: 6, 9, 12, 15, and 18 mm. These known target depths were compared to target depths measured in the simulated photoacoustic images.

Simulation results were compared to theoretical values using the following expression derived from a two-layer phantom model containing temporal bone located between a transducer and cranial tissue:

$$d_{measured} = d_{actual} + t_b\left(\frac{c_0 - c_b}{c_b}\right), \qquad (1)$$