A novel drill design for photoacoustic guided surgeries

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ABSTRACT

Fluoroscopy is currently the standard approach for image guidance of surgical drilling procedures. In addition to the harmful radiation dose to the patient and surgeon, fluoroscopy fails to visualize critical structures such as blood vessels and nerves within the drill path. Photoacoustic imaging is a well-suited imaging method to visualize these structures and it does not require harmful ionizing radiation. However, there is currently no clinical system available to deliver light to occluded drill bit tips. To address this challenge, a prototype drill was designed, built, and tested using an internal light delivery system that allows laser energy to be transferred from a stationary laser source to the tip of a spinning drill bit. Photoacoustic images were successfully obtained with the drill bit submerged in water and with the drill tip inserted into a thoracic vertebra from a human cadaver. Possible clinical applications include spinal fusion surgeries and orthopedic surgeries in general.

Keywords: spine surgeries, orthopedic surgeries, photoacoustic guidance, light delivery

1. INTRODUCTION

Spinal surgeries are some of the most common operations performed. In particular, 150,000 Spinal Fusions are performed each year[1] and 90 out of every 100,000 Medicare enrollees have had a vertebroplasty.[2] These and other spinal procedures are primarily guided by fluoroscopy or repeated C-arm X-rays, which exposes the surgeons, operators, and patients to ionizing radiation.[3] For vertebroplasty and kyphoplasty, radiation exposure from intraoperative fluoroscopy can cause an additional 410 cases of cancer per 1 million patients[4] with the risk increased for younger patients or patients who may have children in the future as the radiation is predicted to increase the risk of birth defects. In addition, x-ray modalities cannot visualize soft tissues such as nerves and blood vessels without the use of contrast agents. As a result, approximately 3% of all spinal fusion surgeries (or about 5,000 each year) result in nerve damage. In addition, spinal fusion surgery sometimes results in blindness when the combination of the placement of the fusion mass and the patient position during surgery cause an ischemic injury.[5]

Based on these existing clinical challenges, there is a clear need for intraoperative imaging that is simultaneously able to visualize critical structures such as nerves and blood vessels while also not adding to the patient and surgeons cumulative radiation dose. Ultrasound imaging has the benefit of being low cost and radiation-free, however the high acoustic reflection caused by the bone interface obstructs visibility of structures beyond the surface of vertebrae.

Photoacoustic imaging is an emerging medical imaging modality that has demonstrated potential to visualize critical structures like blood vessels and nerves as well as surgical tools without requiring harmful ionizing radiation. Thus, there is great potential for photoacoustic imaging to assist with surgical tool tracking and visualization during spinal surgeries. Previous work demonstrates a method to augment surgical tools, in particular a neurosurgical drill,[6] with an external laser light delivery system, allowing for generation of photoacoustic signals at the drill tip location. While this work demonstrates an important proof of concept, there are several cases where this external light delivery design is insufficient. For example, an external light delivery system requires a "line of sight" between the optical fibers transmitting the laser and the tool tip. An external system also increases the form factor size of the surgical tool on which it is mounted, rendering it unusable when drilling holes deeper than a few millimeters (as the laser light will be absorbed by the surrounding tissues before it can

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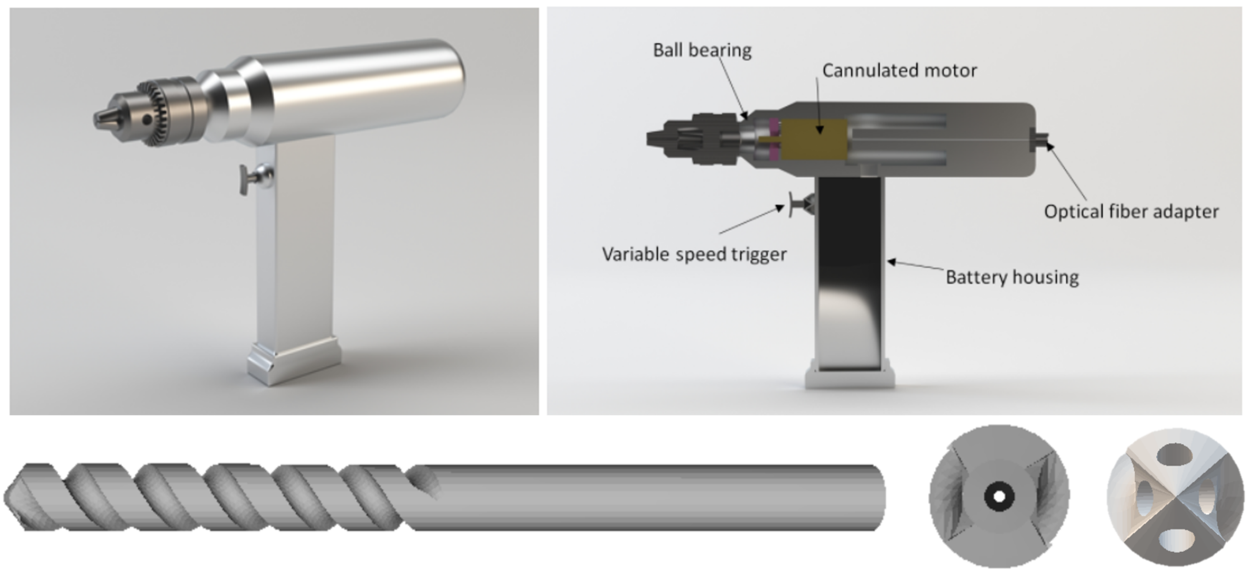


Figure 1. 3D Solid models of drill and drill bit designs. Three possible drill bits include no, one, and more than one holes at the drill tip (shown from left to right, respectively). All drill bits have a hollow core to enable the insertion of an optical fiber.

reach the tool tip). The external design is similarly problematic when it prohibits the surgical tool from reaching the surgical target within the patient.

To address these challenges, we designed a method to transmit laser light to the tool tip internally by proposing a fundamental redesign of the drill bit and drill itself. This paper introduces this novel design and presents a few of our initial results with the drill prototype.

2. METHODS AND MATERIALS

Our drill design consists of three main components. The first and second are two types of drill bit designs, and the third is a drill design to enable the delivery of laser light internally to our drill bits. A 3D model of the overall drill concept, as well as a 3D models of the drill bits are shown in Figure 1.

The first drill bit design is a hollow core drill bit that has a polished glass fiber inserted into the core so that laser light can pass down the core of the drill bit where it is then absorbed internally at the drill bit tip, thereby producing photoacoustic signals to indicate the location of the drill tip. The tip of this drill bit is solid and closed (i.e., no holes) as in standard drill bit designs.

The second drill bit design is a modification of the first design. Instead of a solid, closed tip, the drill bit tip has one or more holes, enabling laser light to travel down the core of the drill bit, then exit the drill bit to illuminate tissue or bone directly in front of the drill bit. This design would result in the generation of a photoacoustic signal both at the drill bit tip as well as in front of the drill bit tip.

Prototype drill bits for these two designs were 3D printed with black resin to preliminarily test the functionality of this design. One drill bit contained a solid tip and the other drill bit contained four holes at the tip. Both had a 1.5 mm hole at the core of the brill bit, and the diameter of the drill bit was 5 mm. A 1 mm core diameter optical fiber was inserted into the hollow core of each drill bit.

In our drill design, a stationary optical fiber connected to an external laser source transfers the laser light to the glass core of the spinning drill bit, making the light appear as one connected profile at high drill bit revolutions (which is important when calculating fluence to determine laser safety). A prototype drill was designed to test the potential use of these new drill bit designs with a stationary laser source and a rotating drill bit, as shown

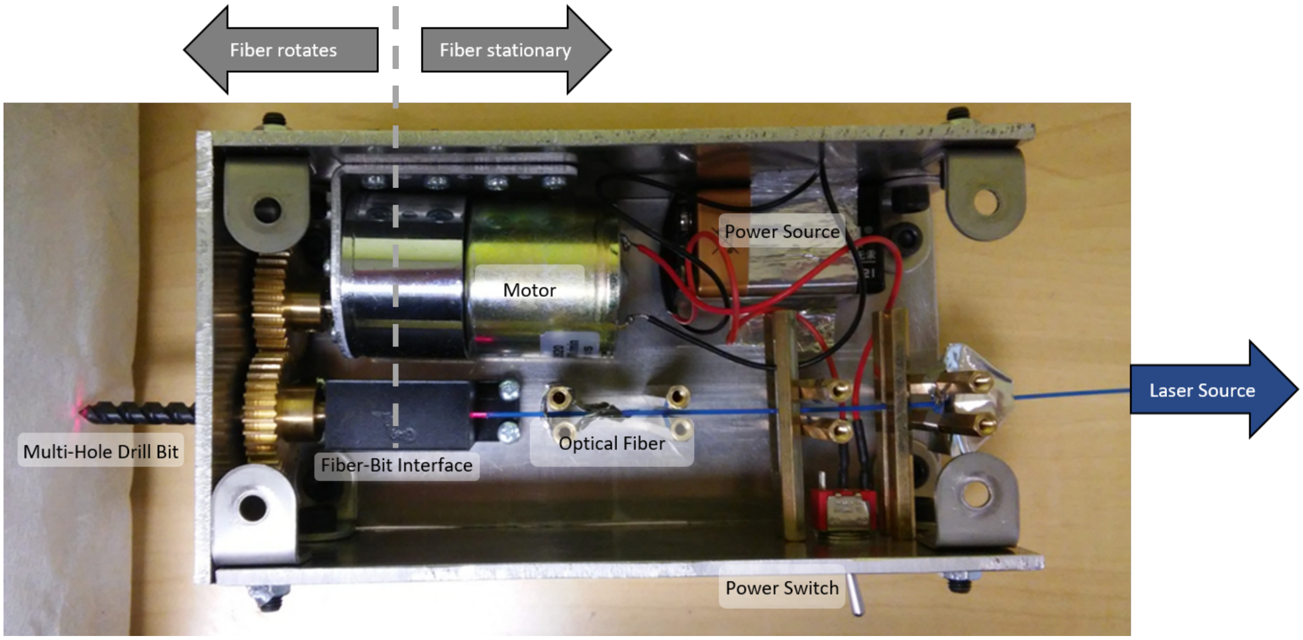
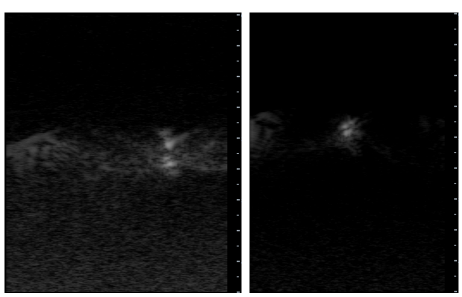


Figure 2. Drill prototype showing the light profile exiting the four-hole drill bit, prior to using the switch to rotate the drill bit and the optical fiber located inside the drill bit.

in Fig. 2. The light transfer takes place inside the critical structure labeled Fiber-Bit Interface in Figure 2. The optical fiber is inserted in one end of the fiber-bit interface, and the drill bit is inserted in the other end with the minimum possible gap between the optical fiber and the glass core of the drill bit to enable light transfer. The holes in this interface were designed and 3D printed to be coincident with each other to ensure fiber alignment on both sides of the interface. This fiber-bit interface can also be incorportated into a new type of motor design to enable a more compact drill as shown in the concept image in Fig. 1.

Note that a standard ultrasound probe is expected to be placed externally to receive the photoacoustic signals. We performed our preliminary testing with the prototypes described above and an Alpinion ultrasound scanner connected to either an Alpinion L3-8 linear array probe or an Alpinion SP1-5 phased array probe. The light source for photoacoustic imaging was an Opotek Phocus Mobile laser source operating at 1064 nm. The energy exiting the fiber tip (measured before it was inserted in the drill bit) was approximately 0.75 mJ.



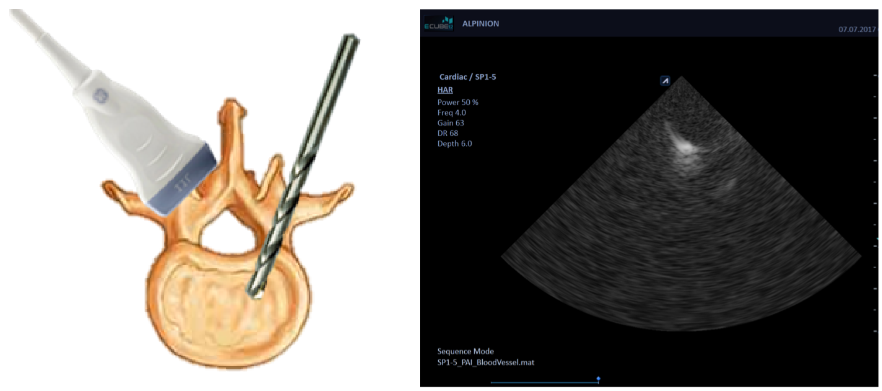
(a) (b)

Figure 3. Photoacoustic images of the drill bit tip in water, demonstrating that it is possible to localize drill tips with our proposed designs. These images were acquired with drill bits containing (a) no holes and (b) four holes at the drill bit tip. Images show 4.5 cm depth and are shown with 60 dB dynamic range.

3. RESULTS

Our prototype drill design was initially tested with the drill tip submerged in water with the goal of determining if the drill tip signal could be visualized in this ideal environment. The photoacoustic signal generated by the solid and multi-hole drill bit tip designs are shown in Figs. 3(a) and 3(b), respectively. These initial results demonstrate that it is possible to localize drill tips with our proposed designs. In addition, the light delivery method successfully works with the drill bit spinning in our prototype design.

We inserted the custom drill bits into a pre-drilled hole inside a cadaveric thoracic human vertebra, as illustrated in Fig. 4(a). The ultrasound probe was placed next to the drill bit in our experiments, although it is shown farther away from the drill bit in Fig. 4(a) for illustrative purposes. The vertebra specimen was submerged in water to provide acoustic coupling for this initial testing of our design. A photoacoustic image of the drill bit in the cadaveric thoracic human vertebra is shown in Fig. 4(b), as acquired with the phased array probe. This image represents the first known detection of photoacoustic signals from within a vertebra.



(a) (b)

Figure 4. (a) Schematic diagram of ultrasound probe placement and drill tip for acquiring a photoacoustic image of the drill bit tip inside a cadaveric thoracic human vertabra. (b) The four-hole drill bit was inserted into the pre-drilled hole in the vertebra and the image is displayed with 68 dB dynamic range.

4. DISCUSSION

We designed, prototyped, and performed initial testing with novel drill components to enable photoacoustic-guided spinal surgeries. The drill contains a novel interface that transfers light from a static laser source to a rotating drill bit. The laser source could be internal to the drill (e.g., with smaller, more-compact, pulsed laser diodes) or external (as implemented for our initial testing). However, an internal, pulsed laser diode would likely not provide the same level of energy as a larger external laser source. Therefore, additional signal processing approaches (e.g, short-lag spatial coherence imaging[7,8]) can be applied to enhance image quality with these smaller, less powerful, internal laser. Potential reflection artifacts from bone interfaces can also be removed with recent deep learning approaches when localizing the drill tip.[9,10]

We additionally designed and 3D printed two novel drill bits to demonstrate potential feasibility. The first design contained a solid tip drill bit where light passes down the core of the drill bit and is absorbed internally at the drill bit tip. The second design was a multi-hole drill bit where light passes down the core of the drill bit and passes through a set of holes in the drill bit tip to be absorbed by both the drill bit and tissues in front of the drill bit.

The prototype drill bits were 3D printed with black resin, but they would ideally be made out of steel or any other suitable metal that absorbs the wavelength used by the laser source. For the multi-hole drill bit design, artificial diamond lenses (or a similar material) created by a chemical deposition method could be embedded into the holes to prevent the drill bit tip from clogging with tissue or bone fragments.

While the prototype drill bit was created with the external form factor shown in Figs. 1 and 2, the same internal light delivery system could be implemented for drill bits in multiple form factors (e.g. different drill diameters, spiral patterns, point angles, lips, or lengths) to enable its use in a wide range of surgical drilling scenarios that are not limited to spinal surgeries.

Possible applications of these designs include a system for segmenting the drill bit location from photoacoustic images and mapping this drill bit location onto a preoperative CT or X Ray to guide drilling. We also envision a system for robustly performing autonomous bone drilling by using the single- or multi-hole drill bit to detect nerves or blood vessels and command the robot controlling the drill to avoid these structures. This system can also be used to implement photoacoustic-based visual servoing[11] with a hand-held drill.

5. CONCLUSIONS

Our internal light delivery drill designs have the potential to simultaneously address two existing challenges during spinal surgeries. The first challenge is to decrease radiation exposure to the patient and surgeon when implementing methods to track the location of the surgical drill. The second challenge is to avoid critical structures such as nerves, blood vessels, and bone boundaries (to avoid breaches) during surgical drilling. The proposed single- or multi-hole drill bit design could be used to detect critical structures before the drill damages them. In addition, the single-hole, multi-hole, or solid tip drill bit designs can possibly be used to direct drilling without the need for continuous intraoperative radiation-based imaging. Although our designs are presented in the context of spinal fusion surgery, similar designs would be applicable to orthopedic surgeries in general.

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