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Penetration of CO₂ laser into the otic capsule using a hand-held, flexible-fiber delivery system

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Abstract

Background and Objective—A new, flexible-fiber, CO₂ laser deliver system has recently been introduced into clinical use. For ear surgery applications, no data has been reported correlating power settings to depth of penetration into otic capsule such as that which covers the cochlea. Our goal in this study was to document such.

Study Design/Materials and Methods—Eight (8) cadaveric temporal bones were procured as per our institution's protocols. For each specimen, 9 different laser holes were burned into the bone overlying the cochlea using the flexible-fiber CO₂ laser. Power settings were varied from 10–20 Watts in 2 Watt increments, and duration of exposure was either 100, 200, 300, 400, or 600 mSec. Each setting (power and duration) were tested on 2 specimens. Following laser exposure, each specimen was scanned in a microCT scanner and the depth of penetration measured from these images.

Results—Of the 72 laser shots, 8 were excluded due to double hits (4) or oblique hits (3) or complete penetration to perilymph (1). After excluding these 8, bone penetration was found to vary from 160 to 670µm based on power and time settings. Spearman analysis on ranked data showed that time had a greater impact on depth than power. The correlation coefficients for time and power were 0.84 ($p = 0.013$) and 0.40 ($p < 0.001$), respectively.

Conclusion—The flexible-fiber CO₂ laser is useful in ear surgery for ablation of soft tissue and bone. However, higher power setting and longer pulse durations can lead to complete penetration of the otic capsule causing damage of underlying structures such as the facial nerve, horizontal semicircular canal, and cochlea.

Keywords

carbon dioxide laser; otologic surgery; depth of penetration; temporal bone; power settings

Introduction

The carbon dioxide (CO₂) laser has been used extensively in the field of otolaryngology for over three decades[(1)]. Current otolaryngologic applications include removal of malignancies of the upper aerodigestive tract [(2)], treatment of laryngeal polyps and papillomas [(2;3;4)], middle ear surgery [(5–10)], and tonsillectomy [(11–13)].

Perhaps the biggest limitation of the CO₂ laser is its inability to be delivered via glass fiber. Glass and other similar synthetic materials have maximal absorption at 10,000 nm which is also the wavelength of the CO₂ laser (10,600 nm). Thus, applications have been limited to “line-of-sight” uses. This includes operating microscopes which fulfill the “line-of-sight” requirement using rigid articulating arms with precisely-positioned mirrors at each joint.

Recently, a new CO₂ laser delivery system has been developed consisting of a flexible-fiber with a mirrored hollow core. This system, commercially available from OmniGuide, Inc. (Cambridge, MA), has found increasing usage in otolaryngology, especially oncologic resection [(14–17)]. Given that the flexible-fiber eliminates the need for “light-of-sight” use, it is ideally suited for otology where tissue is often hidden behind boney ledges. Case reports have attested to its utility in middle ear surgery [(18)]. Lacking, however, are detailed studies correlating laser power and duration of exposure to depth of penetration within the middle ear—vital information if one is to limit damage to collateral tissue especially the facial nerve, cochlea, and semicircular canals.

The otic capsule bone was chosen as the target bone for our study of the new CO₂ laser system. The laser is already being used in otologic surgery in the middle ear and on the promontory (ie. lateral surface of the cochlear otic capsule bone) for ablation and excision of glomus tympanicum tumors. These are very vascular tumors and excision often requires firing the laser into briskly bleeding vessels on the promontory. At this time we are unaware of how much power the promontory can absorb, without risk of penetrance into the perilymph of the cochlea. Additionally, the laser may provide a novel method for cochleostomy in future cochlear implants. By using cadaveric otic capsules, we sought to determine the effect of increasing power and pulse duration on the otic capsule bone, to ascertain safety and amounts of bone ablation.

Material & Methods

Specimens

Eight temporal bones from the body donation program of our institution were harvested for this study. All temporal bones were fresh frozen. The labyrinth and the cochlea were cut out of the temporal bone to (1) allow the specimens to fit into the microCT scanner (described below) specimen holder and (2) allow unimpeded access to the otic capsule for laser application. Temporal bone specimens were removed from the freezer and allowed to warm to room temperature for 1 hour prior to experiments.

Institutional Review Board (IRB) approval was not sought as experimentation on cadaveric specimens is not considered human research by the Office for Human Research Protection.

Laser Apparatus

A NovaPulse, 20-watt CO₂ laser (Lumenis Inc; Santa Clara, CA) was utilized in this study. The factory installed mirror arm of the NovaPulse was replaced with an adapter for the OmniGuide fiber (BeamPath™ OTO-S Fiber, OminiGuide; Cambridge, MA). The OmniGuide fiber is a photonic bandgap fiber whose inner surface is a dielectric mirror with alternating layers of low and high reflective index providing near-total internal reflection [(4;19;20)]. The fiber has an outer diameter of 1.5mm and inner diameter of 0.5mm. It is directed to a surgical target using a hand piece consisting of malleable aluminum (Steiner hand piece; Karl Storz, Germany) through which the fiber is thread. Helium gas is perfused through the fiber at a rate of approximately 2 L/min to both prevent occlusion by ablated material and cool the fiber. Working distance is between 2 and 5 mm from the fiber tip.

Experimental Procedures

On each cochlea 9 laser shots were made into the otic capsule in close proximity to the round window niche (Figure 1). The power was varied between 10 and 20 W in 2W increments. Laser pulse duration was set at either 100mSec or 200mSec; to achieve higher times, laser shots were repeated to achieve 300, 400, and 600mSec durations. Each test condition, specified by the power and duration, was repeated on 2 specimens. Table 1 summarizes the test conditions studied.

microCT imaging

Post procedure imaging was performed using the Scanco microCT 40 (SCANCO MEDICAL AG; Bassersdorf, Switzerland). This table-top, cone-beam CT scanner allows imaging resolution down to 10 µm. As the maximum field of view is a cylinder 80mm by 36.9mm, each specimen was dissected down to this size preserving the cochlea and labyrinth prior to laser application. The image matrix of the post-processed images in DICOM3 format were 1024 × 1024 × (slice number) pixels with slice numbers between 500 and 600 depending on the individual anatomy of each specimen; pixels were isotropic and measured 36 µm on each edge. Through iteration we determined an optimal source power of 30kVp/40keV at 120 µA.

Analysis

Images were viewed in proprietary software developed at our institution but could also have been performed on non-proprietary image viewer software such as 3-D Slicer (www.slicer.org). After importing the DICOM 3 files, three dimensional (3D) volumes were created allowing both surface renderings and generation of 2 dimensional (2D) slices at any orientation. Surface renderings were used for orienting specimens to determine test conditions (Figure 1b). Following this, 2D slices were aligned to the axis of the laser hole to determine depth of penetration (Figure 3); these images were magnified by 5 and digital measurements were made with precision of 0.01 mm. As each test condition was performed twice, average depth was calculated and used in data presentation. Laser shots where a “double-shot” (Figure 3, panel B) or an “oblique shot” (Figure 3, panel C) occurred were excluded from analysis. For test conditions where only a single data point was obtained, no averaging occurred.

Data was analyzed using SPSS software (Version 17.0; Chicago, IL) to perform Spearman correlation on ranked data. As a further test, a multiple regression analysis on ranked data was performed to control for the interaction of time on power and vice versa, but was found to not differ significantly from the Spearman analysis.

Results

Of the 72 laser shots on the either cochlear specimens, 8 were excluded due to double hits (4) or oblique hits (3) or complete penetration to perilymph (1) (Figure 3). Depth of laser strikes varied between 160µm and 670µm as shown in Figure 4 where depth of penetration is shown with respect to laser power for each set of pulse duration (e.g. 3 × 200 msec pulses is shown in the clear circle data points). Grouping all data, Spearman rank correlation revealed correlation coefficients of 0.84 for time ($p < 0.001$) and 0.40 for power ($p = 0.013$) thus resulting in the following empiric formula for depth of penetration:

$$\text{Depth (in mm)} = 0.84 (\text{duration of laser in msec}) + 0.40 (\text{power in W})$$

Discussion

In general, three types of laser find are used in otolaryngology: KTP (532nm), CO₂ (10600 nm), and Er:YAG (2940 nm)[(22)]. The KTP laser is strongly absorbed by hemoglobin, making it an excellent tool for homeostasis. As KTP lasers are easily guided through fibers, they are widely used for soft tissue surgery such as endoscopic approaches to the upper aerodigestive tract. However, the pigmentation of the middle ear is less than ideal for KTP laser absorption. The white stapes footplate only partially absorbs KTP laser and risk exists for penetration into the vestibule where pigmented structures (e.g. microvasculature) may be damaged by energy absorption [23]. The Er:YAG laser is a pulsed laser which emits short bursts of high power density within a microsecond. This so called “photoablation” process produces micro-explosions which results in acoustic shock waves limiting its use for middle ear surgery [(24;25)].

The CO₂ laser is an effective and widely used surgical tool in Otolaryngology. It can vaporize thin bony structures when focused to a small spot, often used to create a stapedotomy. One of the main advantages of the far-infra red emission of the CO₂ laser is its strong absorption by water, resulting in shallow penetration (< 0.01nm) from the target surface. This property of CO₂ laser light is particularly useful in stapes surgery where bone and perilymph completely absorb the CO₂ laser energy limiting deeper penetration and collateral damage. To date, the biggest drawback of CO₂ laser has been the need for line-of-sight applications. This is especially frustrating as CO₂ lasers are invisible and one must depend upon an aiming beam to be accurately aligned to the CO₂ source.

The development of the flexible-fiber CO₂ delivery systems is a large advance in the field as it allows the benefits of the CO₂ laser without the drawbacks. As such, it is ideally suited for middle ear surgery and case reports from the manufacturer attest to its usefulness (www.omniguide.com). However, we must remain cognizant that the tool remains a laser with risks of over-penetration and collateral damage. We undertook this study to determine

the relationship between power, pulse duration, and depth of penetration into the otic capsule.

While this pilot study has limited sample sizes, figure 4 does show a trend relating power to depth of penetration that was repeatable. This first report relating depth of penetration with power and duration shows that high settings (eg. 20 watts and multiple 200msec pulses) can result in complete penetration of the labyrinth. However, lower power and pulse duration settings (eg. 10–18 watt and 100msec pulses) were shown to be safe in not violating the labyrinth in over 26 experiments with our cadaveric specimens. These power settings are much higher than those recommended by the manufacturer (ie. 4 watts at 100msec pulses for stapes surgery) suggesting that there is a large margin of safety at low settings.

Conclusion

The fiber guided CO₂ laser is an effective and adaptable surgical tool in for middle ear work. The depth of the bone ablation could be verified for different pulse rates and energy settings. Further studies on temporal bones need to be performed to demonstration dedicated surgical indications including stapedotomy and cochleosotomy with specific parameters (power, pulse duration) for each application.

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References

1. Strong MS, Jako GJ. Laser surgery in the larynx Early clinical experience with continuous CO₂ laser. *Ann Otol Rhinol Laryngol*. 1972; 81(6):791–798. [PubMed: 4636137]
2. Wang Z, Devaiah A, Feng L, Dasai U, Shapira G, Weisberg O, et al. Fiber-Guided CO₂ Laser Surgery in an Animal Model. *Photomedicine and Laser Surgery*. 2006; 24(5):646–650. [PubMed: 17069498]
3. Jacobson AS, Woo P, Shapshay SM. Emerging technology: flexible CO₂ laser WaveGuide. *Otolaryngol Head Neck Surg*. 2006; 135(3):469–470. [PubMed: 16949984]
4. Zeitels SM, Kobler JB, Heaton JT, Faquin W. Carbon dioxide laser fiber for laryngeal cancer surgery. *Ann Otol Rhinol Laryngol*. 2006; 115(7):535–541. [PubMed: 16900808]
5. Jovanovic S, Schonfeld U. Application of the CO₂ laser in stapedotomy. *Adv Otorhinolaryngol*. 1995; 49:95–100. [PubMed: 7653395]
6. Jovanovic S, Schonfeld U, Scherer H. CO₂ laser stapedotomy with the “one-shot” technique—clinical results. *Otolaryngol Head Neck Surg*. 2004; 131(5):750–757. [PubMed: 15523460]
7. Lesinski SG, Palmer A. CO₂ laser for otosclerosis: safe energy parameters. *Laryngoscope*. 1989; 99(6 Pt 2 Suppl 46):9–12. [PubMed: 2498590]
8. Lesinski SG, Stein JA. CO₂ laser stapedotomy. *Laryngoscope*. 1989; 99(6 Pt 2 Suppl 46):20–24. [PubMed: 2498589]
9. Wang Z, Jiang Y. Cochlear microendoscopy and CO₂ laser vaporization during cochlear implantation. *Adv Otorhinolaryngol*. 2000; 57:106–108. [PubMed: 11892119]
10. Williams DJ, Hunter-Duvar IM, Mitchell DP. Use of the CO₂ laser in otology. *Ann Otol Rhinol Laryngol*. 1981; 90(1 Pt 1):70–71. [PubMed: 6781397]
11. Baharudin A, Shahid H, Rhendra MZ. Laser tonsillotomy in children with tonsillar hyperplasia. *Med J Malaysia*. 2006; 61(3):377–379. [PubMed: 17240597]

12. Densert O, Desai H, Eliasson A, Frederiksen L, Andersson D, Olaison J, et al. Tonsillotomy in children with tonsillar hypertrophy. *Acta Otolaryngol.* 2001; 121(7):854–858. [PubMed: 11718252]
13. Unkel C, Lehnerdt G, Schmitz KJ, Jahnke K. Laser-tonsillotomy for treatment of obstructive tonsillar hyperplasia in early childhood: a retrospective review. *Int J Pediatr Otorhinolaryngol.* 2005; 69(12):1615–1620. [PubMed: 16191441]
14. Devaiah AK, Shapshay SM, Desai U, Shapira G, Weisberg O, Torres DS, et al. Surgical utility of a new carbon dioxide laser fiber: functional and histological study. *Laryngoscope.* 2005; 115(8): 1463–1468. [PubMed: 16094126]
15. Holsinger FC, Prichard CN, Shapira G, Weisberg O, Torres DS, Anastassiou C, et al. Use of the photonic band gap fiber assembly CO2 laser system in head and neck surgical oncology. *Laryngoscope.* 2006; 116(7):1288–1290. [PubMed: 16826079]
16. Holsinger FC, Weber RS. Swing of the surgical pendulum: a return to surgery for treatment of head and neck cancer in the 21st century? *Int J Radiat Oncol Biol Phys.* 2007; 69(2 Suppl):S129–S131. [PubMed: 17848281]
17. Solares CA, Strome M. Transoral robot-assisted CO2 laser supraglottic laryngectomy: experimental and clinical data. *Laryngoscope.* 2007; 117(5):817–820. [PubMed: 17473675]
18. Otology & Neurotology: OmniGuide Case Report. <http://www.omni-guide.com/beam-path-technology-papers-and-publications.htm>. November 14, 2008. Ref Type: Internet Communication
19. Ibanescu M, Fink Y, Fan S, Thomas EL, Joannopoulos JD. An All-Dielectric Coaxial Waveguide. *Science.* 2000; 289(5478):415–419. [PubMed: 10903194]
20. Temelkuran B, Hart SD, Benoit G, Joannopoulos JD, Fink Y. Wavelength-scalable hollow optical fibres with large photonic bandgaps for CO2 laser transmission. *Nature.* 2002; 420(6916):650–653. [PubMed: 12478288]
21. Labadie RF, Noble JH, Dawant BM, Balachandran R, Majdani O, Fitzpatrick JM. Clinical validation of percutaneous cochlear implant surgery: initial report. *Laryngoscope.* 2008; 118(6): 1031–1039. [PubMed: 18401279]
22. Hüttenbrink, KB.; Ambrosch, P.; Telger, TC. *Lasers in Oto-Rhino-Laryngology.* 1. Stuttgart: Georg Thieme Verlag; 2004.
23. Lesinski SG. Lasers for Otosclerosis – Which One if Any and Why? *Lasers Surg Med.* 1990; 10(5):448–57. [PubMed: 2233099]
24. Gardner EK, Dornhoffer J, Ferguson S. Photoacoustic effects of carbon dioxide lasers in stapes surgery: quantification in a temporal bone model. *Otol Neurotol.* 2002; 23(6):862–865. [PubMed: 12438847]
25. Wong BJ, Dickinson MR, Berns MW, Neev J. Identification of photoacoustic transients during pulsed laser ablation of the human temporal bone: an experimental model. *J Clin Laser Med Surg.* 1996; 14(6):385–392. [PubMed: 9467330]

Figure 1. Laser shots in 3×3 matrix on the otic capsule. Each spot was shot with a different energy and a different duration. Arrow indicates round window of the cochlea. Bracket shows the 3×3 laser shot matrix.

Figure 2.
Micro CT analysis of the laser shots. Lesions produced with 12 W, 14 W and 16 W at 200 msec.

FIGURE 3.

“Double-shot” occurred when repeat shots did not hit the exact center of the crater. Double-shots were noted in 4 of the 72 (5.6%) test conditions and were excluded from data analysis.

B: “Oblique shots” were not perpendicular to the surface of the otic capsule. Oblique shots were noted in 3 of 72 (4.2%) test conditions and were excluded from data analysis.

C. Complete penetration of otic capsule occurred in 1 specimen with power of 20 W and 400 msec duration (2×200 msec) and was not included in data analysis.

Figure 4.
Fiber guided CO₂ Laser ablation of the otic capsule at different laser energy levels and duration of the treatment.

Table 1

Experimental Protocol: Test conditions consisted of one power setting (10 – 20 Watts in 2 W increments) and one pulse duration setting (100, 200, 300, 400, or 600 msec). Each condition was tested on 2 specimens.

POWER	PULSE DURATION				
	100 msec		200 msec		
10, 12, 14, 16, 18, or 20 Watts	1 pulse (100 × 1 = 100 msec)	2 pulses (100 × 2 = 200 msec)	3 pulses (100 × 3 = 300 msec)	1 pulse (200 × 1 = 200 msec)	2 pulses (200 × 2 = 400 msec) 3 pulses (200 × 3 = 600 msec)