Otology & Neurotology
35:1070–1076 © 2014, Otology & Neurotology, Inc.

Capturing Thermal, Mechanical, and Acoustic Effects of the Diode (980 nm) Laser in Stapedotomy

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Introduction: The diode laser, with a wavelength of 980 nm, has promising characteristics for being used for the fenestration during stapedotomy. It is known that at this wavelength absorption in pigmented tissues is high, and absorption in water is relatively low compared with medical lasers in the infrared, making it theoretically an applicable laser for stapes surgery in patients with otosclerosis. Another important advantage is that, with respect to other lasers, this device is relatively inexpensive. Despite the potential advantages, the available literature only shows limited reports of this laser being used in stapes surgery. The present article evaluates the thermal, mechanical, and acoustic properties of the diode laser during stapes surgery.
Methods: For the mechanical effects, high-speed imaging with a frame rate up to 4000 f/s (=250 μs resolution) was performed in an inner ear model. For thermal effects, the high-speed Schlieren technique was used. Acoustics were recorded by a hydrophone, incorporated in the model. Pulse settings were 100 ms, 3 W, which are the same settings used during stapes surgery.
Results: The application of the diode laser resulted in limited mechanical and thermal effects. Impulse noise was low with an average of 52 (SD, 7.8) dB (A). Before carbonization of the tip of the delivery laser, fiber enhances ablation of the footplate.
Conclusion: The 980-nm diode laser is a useful tool for laser-assisted stapedotomy in patients with otosclerosis. Mechanical, thermal, and acoustic effects are limited and well within the safety limits. **Key Words:** Diode—Hearing—Laser—Otosclerosis—Stapedotomy—Trauma.
Otol Neurotol **35:**1070–1076, 2014.

Argon laser stapedotomy was first introduced by Perkins in 1980 (1). Performing the fenestration of the footplate with a laser has proven to be safer than the use of traditional instruments (2). Until now, various lasers have been proposed to be safe for use in stapedotomy. However, each of these lasers has its own specific characteristics, which influence its potential risk to damage the inner ear structures.

The traditionally used lasers, such as the argon (488 nm) and KTP (532 nm) laser, bear the risk of damaging the inner ear. Because of their light transmission through watery liquids, such as the perilymph, unwanted energy is absorbed at the pigmented area of the neuro-endothelium of the vestibule. The pulsed Er:YAG laser (2940 nm) ablates bone with explosions, causing a sound pressure wave, which is considered potentially traumatic to inner-ear hair cells by some surgeons (3,4). The CO_2 laser (10600 nm), used in both continuous wave and pulsed wave mode, is well absorbed in both fluid and bone, causing a controlled perforation. Excess energy is highly absorbed by the perilymph and therefore will not reach the neuroendothelium (5,6). Recently, hollow waveguides have been introduced for CO2 lasers; instead of delivering the CO_2 laser beam as a free beam through an articulated arm, the beam is transmitted through a flexible hollow air core fiber. Waveguides allow direct delivery of energy to the tissue. Drawbacks are the costs of these systems and the fragility of the somewhat bulky fiber.

The first report in the ENT literature of the Diode laser was in 2000 (4). The diode laser consists of a semiconductor device, producing coherent radiation in the infrared spectrum. Because of its high efficiency, it can generate high-energy output while limited energy is supplied. Even small, battery-powered, hand-held devices can produce the necessary energy fluences. The 800- to 1064-nm wavelengths are most commonly used in medical practice and can be easily fiber delivered. Absorption characteristics include high absorption in pigmented tissues and low absorption in water compared with the CO_2 and Er-YAG laser. Compared with KTP laser, it has much

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Supplemental digital content is available in the text.
The authors disclose no conflicts of interest.

higher absorption in water. These characteristics potentially make it a suitable laser for otosclerosis surgery. After fenestration of the footplate part of the excessive energy will be absorbed in the perilymph. The remaining energy will be absorbed in the pigmented region of the neuroendothelium, although it is much less, compared with the argon and KTP-laser (7). Current applications of the diode 980-nm laser include hair removal, treatment of port wine stains, and treatment of epistaxis in selected cases (8–10).

The aim of this study is to investigate the thermal, mechanical, and acoustic effects of the diode laser, with a wavelength of 980 nm, in an inner ear model.

MATERIALS AND METHODS

Inner Ear Model

To visualize the effects in the vestibule during perforation of the footplate, experiments were performed in an inner ear model. A schematic drawing of the inner ear model used for our experiments is shown in Figure 1. A slab of transparent polyacrylamide gel was sandwiched between 2 glass windows. These glasses are tightly slid in a plastic holding container. A 3-mm deep artificial vestibule was created in the gel, corresponding to the depth of the human vestibule. The artificial vestibule was filled with NaCl 0.9%, mimicking the perilymph. A NaCl solution was used because it has the same light absorption properties as perilymph. A small strip of dialysis membrane, with a small central perforation, was placed over the artificial vestibule. A fresh frozen human cadaver stapes footplate was placed directly on top of the perforation in the dialysis membrane, thereby ensuring that the footplate is in direct contact with the fluid. The dialysis membrane keeps the footplate from sinking. No more than 4 perforations were made per stapes (not overlapping) and a total of 10 stapes were used. The model was placed in the imaging setup. All tests were conducted in room temperature. The fiber tip of the diode laser was placed directly onto the footplate before firing the laser.

Mechanical Effects

Mechanical effects as a result of perforation occurred within the first milliseconds after the laser pulse. The frame rate of conventional imaging is not sufficient to register the effects that occur in a time frame this small. Therefore, high-speed imaging was used instead. Using a high-intensity white illumination source, a frame rate of 4,000 frames per second (f/s) (=250 μs resolution) was obtained. Furthermore, high-speed imaging allowed us to use different viewing angles and capture processes occurring around the footplate and in the vestibule. For each laser setting, 3 holes were created in the stapes to confirm reproducibility of the observed effects. The video clips were examined by 2 authors (D. M. A. K. and T. d. B.) and scored on particle, plume, and bubble formation.

Thermal Effects

A special optical technique based on color Schlieren imaging was used to study the thermal effects (11,12). This technique visualizes inhomogeneities in the refractive index of a transparent medium induced by, for example, temperature gradients. Light rays passing through water or a transparent tissue phantom will be deflected when a temperature gradient, caused by laser-induced heating, is present. The undeflected and deflected rays are focused onto a rainbow filter by an imaging lens. This produces a colored ‘‘thermal’’ image showing the presence and dynamics of the temperature gradient in real time. These thermal images do not show absolute temperatures but rather the relative local temperature dynamics. Using a high-intensity white illumination source, frame rates up to 1000 f/s (at 1 ms resolution) were obtained. In contrast: a ‘‘standard’’ thermal camera can only typically detect surface temperatures at a frame rate of 25 f/s (at 40-ms resolution). This technique also enables the visualization of temperature effects inside a physiologic medium like water and can be combined with a regular high-speed camera at high magnification using standard close-up optics. The same test setup was previously described and used to visualize thermal effects of the KTP, CO_2, and thulium laser (12).

A camera filter was used during the experiments to protect the high-speed camera, as video cameras are highly sensitive for the infrared light. Three fenestrations were created in the stapes to confirm reproducibility of the observed effects. The video clips were examined and ranked independently by 2 of the authors (D. M. A. K. and T. d. B.), after which, results were compared. Discrepancies between independent rankers were resolved by discussion, and reported results are based on full consensus.

In this article, video stills will be represented of the imaging obtained. The high-speed imaging videos will be accessible online as Supplemental Digital Content (SDC).

Acoustic Effects

The sound production was measured using a hydrophone (Kingstate, Omni, sensitivity -42 ± 3 dB, maximum frequency range 25–20,000 Hz, diameter 6 mm), which was placed 1 cm below the stapes footplate.

Recordings were made during 100 ms after onset of the laser pulse. The hydrophone was calibrated with a reference source (Blaupunkt speaker, PCxb352) presenting pure tones over the whole frequency range (125 Hz to 16 kHz) at 10 cm distance from the hydrophone. Sound levels were determined with a sound level

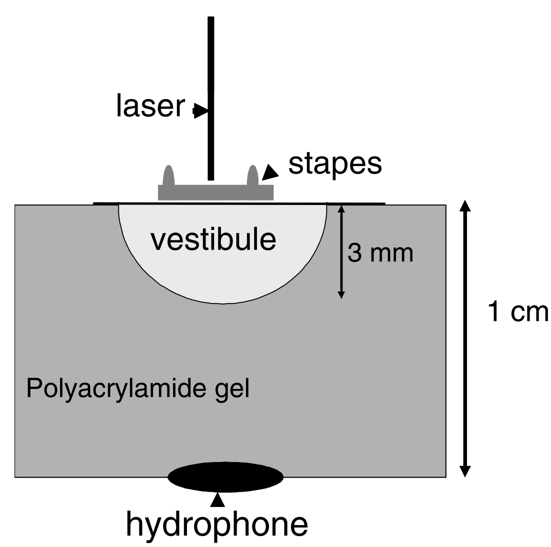

FIG. 1. Inner ear model as seen by the high-speed camera. The inner ear model consists of a polyacrylamide gel with an artificial vestibule, a fresh frozen human stapes, and a laser fiber. A hydrophone is placed 1 cm below the stapes footplate. This model was contained in a glass container and placed in the image setup.

meter (Brüel and Kjær, 2203) and a 1-inch microphone (Brüel & Kjær, 4132). For each laser fenestration, a 100-ms audioclip was recorded. The data were analyzed using custom-written software in Matlab 7.6 (the Mathworks, Inc) programming environment. Within the raw data, the 10 ms with highest amplitudes were analyzed. Over this time frame, a frequency analysis was performed (Fourier analysis), breaking the signal into 1/3-octave bands. The peak frequency, that is, the frequency with the highest sound level, was identified. The level of this peak was converted into dB (A). This A-weighting makes is possible to identify the damaging characteristics of a sound, according to its frequency, as the ear is not equally sensitive for all frequencies. Converting to dB (A) makes it possible to compare the potential harm of the sound produced by different lasers.

In a previous experiment, a 532 nm KTP laser (IDAS, Quantel Derma, Erlangen, Germany), a 2-μm continuous wave (''thulium'') laser (LISA laser, Katlenburg, Germany) and a 10.6-μm continuous wave CO_2 laser (A.R.C. laser, Nurnberg, Germany) were already tested. Settings were conform clinical practice; KTP 1 W, 100 ms, fiber 200 micron; thulium 5 W, 100 ms, 372 micron fiber; CO_2 2 W, 100 ms, and 250 nm hollow wave guide. A flow with helium gas was delivered through the center of the hollow wave fiber (>1 bar) to prevent pollution of the fiber core. All lasers were tested in the same testing paradigm as the diode laser.

The results of all these recordings were analyzed per laser group. Statistical analyses were performed by means of repeated-measures analysis of variance (rm ANOVA), using SPSS for Windows (version 20.0); p <0.05 was considered statistically significant.

The sound recordings of the laser experiments were compared with the sound production of a Osseostap microburr, 8 mm diamant drill (Bien-Air, Bienne, Switzerland). In these experiments, the stapes was directly placed on the polyacrylamide gel and fixed between 3 pin needles. Without fixation, the stapes footplate tends to spin with the rotating drill. As the drill needs time to speed up, timeframe of measurement was prolonged to 1 second. Other test settings were the same for all of the experiments.

Laser

A 980-nm hand-held, battery-driven diode laser, with a 200-μm fiber (FOX, A.R.C. Laser Nurnberg, Germany) was used. A single-pulse laser beam of 3.0 Watt was fired for 100 ms in all of the experiments. The total energy over the irradiated surface (fluence) was 955 J/cm^2. Using lower settings will not lead to footplate perforation. These settings correspond with settings currently used in daily ENT practice. Before starting

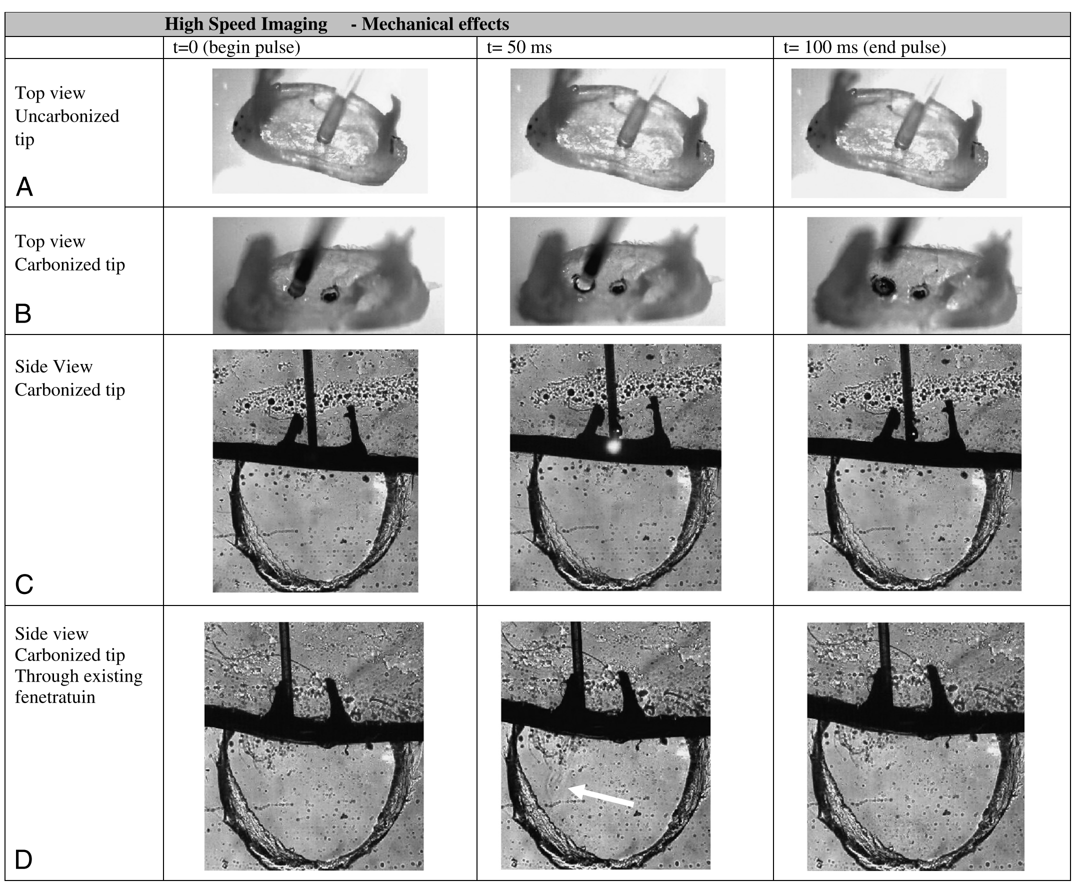

FIG. 2. Mechanical effects, high-speed imaging. Snapshots at t = 0, 50 ms, and 100 ms, during single-shot laser fenestration. Pulse 100 ms at 5 W. *A*, Top view, no carbonization of tip, no effects on footplate. (see also SDC 1, http://links.lww.com/MAO/A202). *B*, Top view, carbonization of tip. Small fenestration with thick carbonized rim (see also SDC 2, http://links.lww.com/MAO/A203). *C*, Side view, carbonized tip. Heating of tip. No mechanical effects (see also SDC 3, http://links.lww.com/MAO/A204). *D*, Side view, carbonized tip, through existing fenestration. In the vestibule, a flow occurs (*white arrow*) (see also SDC 4, http://links.lww.com/MAO/A205).

the experiments, the laser tip was carbonized using the laser on a wooden spatula, at 3 W, 100 ms, 5 pulses.

RESULTS

Mechanical Effects

The 980-nm diode laser wavelength is strongly absorbed in pigmented areas. The white footplate of the stapes is not a pigmented area. We therefore carbonized the fiber tip before firing the laser (see Fig. 2A and Supplemental Digital Content 1, http://links.lww.com/MAO/A202) to optimize bone ablation. After carbonization of the fiber at a different, pigmented location, the fiber was ready for use. This process also needs to be carried out when using the KTP laser. However, when using the KTP laser, carbonization is achieved at a much faster rate. During the pulse, a large area of the stapes footplate was carbonized. A smoke plume formed at the site of the perforation, which is evidently visible in the videos online. A small conical perforation and a large rim of carbonization were seen after the laser pulse (see Fig. 2B and see Supplemental Digital Content 2, http://links.lww.com/MAO/A203).

When looking into the artificial vestibule from the side, only minimal effects were witnessed during the laser pulse. The fiber tip lightened up, because of extensive heating. No effects in the vestibule were seen (Fig. 2C and Supplemental Digital Content 3, http://links.lww.com/MAO/A204). When using the laser through an already existing perforation, a small flow of the NaCl solution could be seen through the vestibule (see the red arrow in Fig. 2D). The movements were better seen on the high-speed imaging video online (Video; see Supplemental Digital Content 4, http://links.lww.com/MAO/A205).

Thermal Effects

When using the diode laser directly on a slab of gel, we could see heat clearly penetrating the gel (see the blue

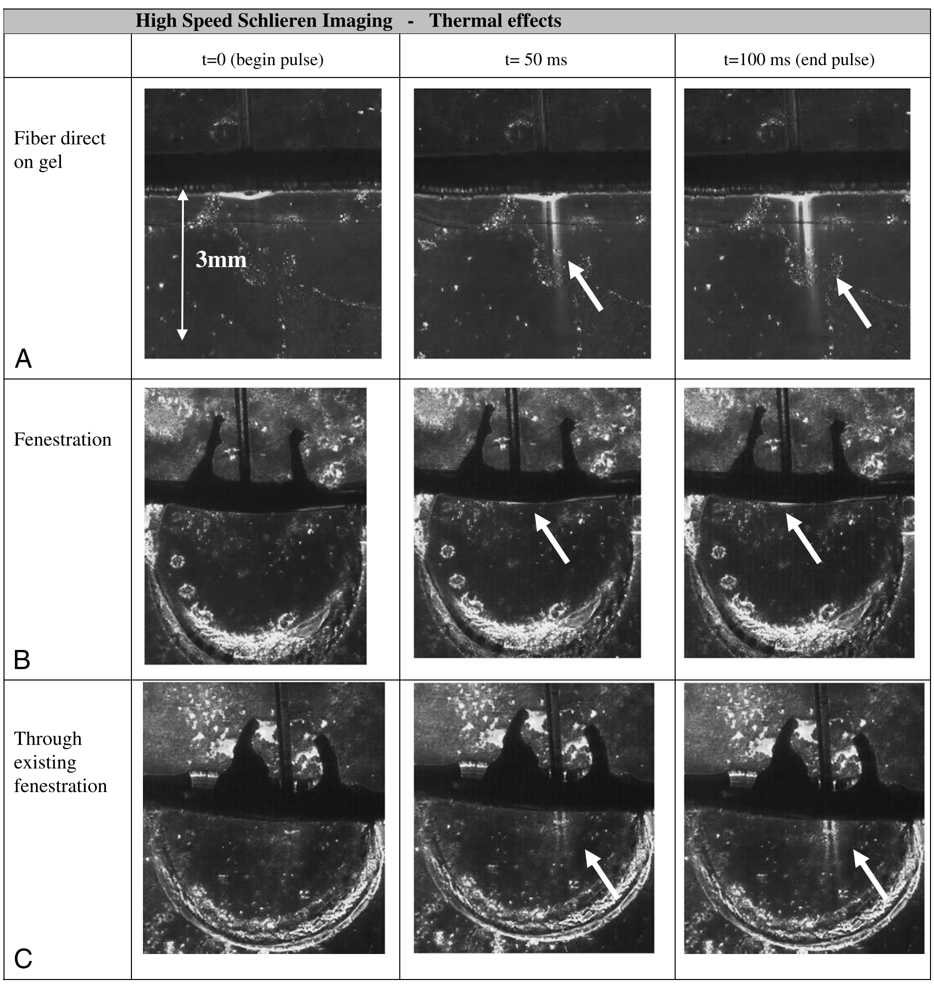

FIG. 3. Thermal effects, high-speed Schlieren. Snapshots at t = 0, 50 ms, and 100 ms, during single-shot laser fenestration. Pulse 100 ms at 5 W. *A*, Fiber direct at gel. Note the penetration depth, *white arrow*. (see also SDC 5, http://links.lww.com/MAO/A206). *B*, Side view of fenestration, with carbonized tip. Note only superficial heating, *white arrow*. (see also SDC 6, http://links.lww.com/MAO/A207). *C*, Side view when laser hits existing perforation. Note the penetration depth, *white arrow* (see SDC 7, http://links.lww.com/MAO/A208).

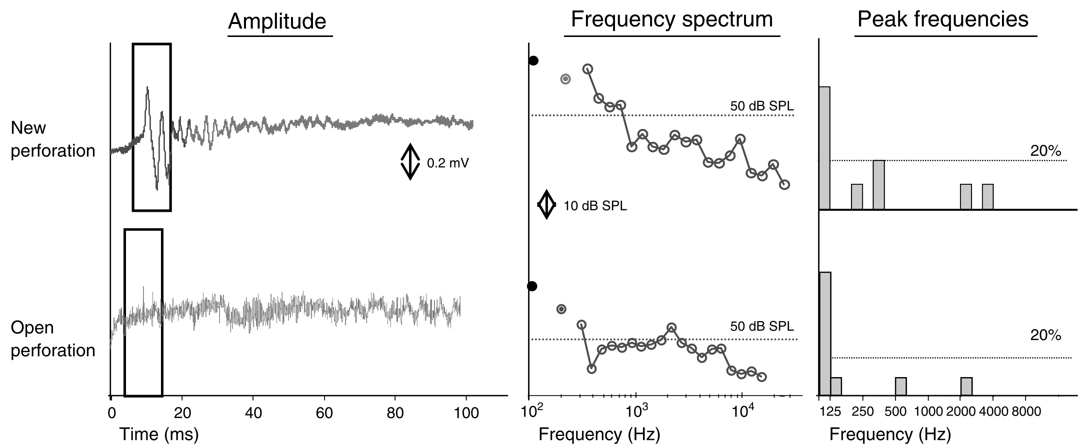

FIG. 4. Acoustic measurements. Two raw audio recordings are shown; one when making a new perforation (top), one when firing through an existing perforation (bottom). Over the time frame of 10 ms with largest amplitudes (box), a frequency spectrum was obtained. This frequency spectrum is shown with a reference line of 50 dB SPL in the central column. Of each spectrum, the peak frequency was located (*black dot*). In the right panel, the peak frequencies were shown for all the measurements taken.

arrow in Fig. 3A and Supplemental Digital Content 5, http://links.lww.com/MAO/A206). A very narrow cone of heat penetrated the gel. Using the Schlieren technique, 2 strips appeared on the video, representing the borders of the cone. When looking at the vestibule from the side, only minimal heating of thec vestibule was seen during perforation of the stapes footplate, just below the footplate (red arrow, Fig. 3B, and Supplemental Digital Content 6, http://links.lww.com/MAO/A207). When a second laser pulse was applied to the same spot, firing into vestibule, the typical penetrating heating pattern was seen again (see blue arrow in Fig. 3C and Supplemental Digital Content 7, http://links.lww.com/MAO/A208).

Acoustic Effects

The diode laser generated limited noise. Fourier analyses showed that the diode laser generated mostly low-frequency sounds, around 100 to 150 Hz. The total loudness of the noise produced during the 100 ms laser pulse was 61 (SD 7.2) dB SPL. The highest impulse noise within this signal, consisted of 52 (SD 7.8) dB(A), at 150 Hz (Fig. 4). This is comparable to the noise produced by the KTP laser and lower than that produced by the CO_2 and thulium laser (Fig. 5) (13). Although the produced sound seems to be rather loud, the traditionally used microburr produces even louder noises. For example, the Osseostap diamond drill (BienAir, Noirmant, Switzerland) generates an impulse noise of 95 (SD 6.9) dB(A) at 2,700 Hz (13). As our hearing is more susceptible for sound at this higher frequency, the potential harmful effects are considered much larger than of low frequency noise.

Using high-speed imaging, flows were seen in the vestibule during laser pulse through an existing perforation only. These movements could have been pressure waves, which are potentially damaging to the saccule. If these pressure waves would have been substantial and thus potentially damaging, they would have resulted in deviations in the raw audio data. We did not identify abnormal results in the audio clips that could have represented pressure waves.

DISCUSSION

In this study, special imaging techniques were applied to visualize mechanical and thermal effects during

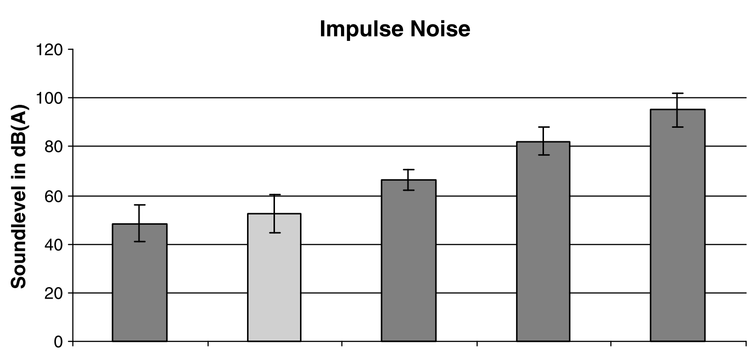

FIG. 5. Comparison of the impulse noise generated by the diode laser, compared with other lasers and drill. The peak frequency of the noise is shown between brackets.

stapedotomy using the diode (980 nm) laser in an inner ear model. It is assumed that damage to the inner ear occurs as a result of heating of the inner ear fluids. Especially larger increases in temperature or prolonged exposure have been associated with vertigo, tinnitus, and hearing loss (14,15). Furthermore, mechanical trauma has been suggested to cause perceptive hearing loss as a result of the formation of sound pressure waves. The mechanical and thermal effects caused by the diode laser were minimal.

We used the Schlieren imaging to measure relative changes in heating at high speed. This technique provides a good insight in the thermodynamic processes inside the inner ear, which give a good prediction of potential damage to inner ear function. When comparing the results of the diode lasers to the lasers that have previously been evaluated by our research group, the same amount of heating was seen in the experiments with the diode laser as was seen in the KTP laser, around 4·C (12). Most researchers use thermocouples to measure heat (16–18). Outcome measurements differ greatly when using thermocouples. The thermocouples only measure heat at 1 distinct point, and the results are highly dependent on the placement of the thermocouples in relation with the stapes footplate. Also, size and material of the thermocouples affect the outcome. During fenestration, the thermocouples can show artifacts because of direct illumination of the laser light. These limitations make thermocouples not ideal for measuring heat, especially when the area of heating is small and exposure time is limited. For the argon laser, temperature increases between 0.4°C (16) and 25°C (19) have been found using different setups. When choosing which laser to use in stapedotomy, a comparative measurement of heating patterns would provide sufficient information.

It is important to note that carbonization of the fiber tip is a requirement for bone ablation. Carbonization of the tip is achieved by firing the laser on a wooden spatula or by using the laser in a vascular area, for instance, superficial muscle. A tip that is not carbonized will not affect the stapes footplate in any way, not even when fluencies are doubled. The main drawback of prior carbonization is that it is not possible to standardize the process of carbonization. The degree of carbonization differs depending on the material used for carbonization and exact distance to the object used for carbonization, laser settings, and so on. The degree of carbonization determines the potency of the laser pulse. The surgeon should have a clear understanding of this mechanism. When the laser pulses seem to have limited ablative effects, this can be resolved by increasing the degree of carbonization of the tip of the laser fiber. This is a helpful technique in avoiding the urge and need for increasing the laser settings. In the future, the use of a commercially blackened tip of the fiber might overcome these problems. Such a blackened tip has been tested in neurosurgical cases and found successful (20).

The carbonization of bone requires temperatures of 200 to 300°C. Although the bone is ablated, some of the heat is transferred to the vestibule. When the same spot is hit twice, the 980-nm wavelength penetrates the vestibule. However, absorption of the 980-nm wavelength in the perilymph is limited. Nonetheless, as with all lasers that are characterized by limited absorption in watery solutions, the diode laser could theoretically damage the well-pigmented cells of the neuro-endothelium. For safety reasons, it seems advisable for the surgeon to avoid shooting on the same spot twice while making the rosette figure on the footplate. We are currently working on a model to investigate this effect in relation to sensorineural hearing loss (SNHL) and to estimate the actual risks.

Only when firing the laser through an existing perforation, a flow occurs in the vestibule. We did not find matching pressure waves in the audio data. These movements have not been described earlier. To understand the possible effects of these movements, special visualizing techniques are needed to visualize them more clearly.

The extent of possible damage due to intraoperative noise production depends on the pulse duration, number of pulses and the frequency and loudness of the sound produced by the laser (21,22). There seems to be a large diversity in individual sensitivity in humans to these impulse noises (21). As a result, there is no general cutoff point that determines when the produced sound is loud enough to result in damage.

The 2940 nm Er-YAG laser is known for its explosive bone ablation, causing impulse noises of 140 to 160 dB(A) (3). In clinical series, some expert surgeons report a decline in bone conduction at 4 kHz up to 8%, whereas others find no change in bone conduction (19,23–26). The sound production of the 980 nm Diode laser is low in all frequencies and therefore neglectable as a source of SNHL.

Overall, in our setup, the 980-nm diode laser generates only minimal side effects and, from that standpoint, can be safely used in clinical settings. Clinical studies need to be undertaken to verify benefits for both patient and surgeons.

CONCLUSION

The diode (980 nm) laser is a useful tool in performing laser-assisted stapedotomy. Mechanical, thermal, and acoustic effects are minimal and well within safety limits.

Because of diode laser high energy-efficient properties, it can be battery operated, which is an advantage when there is limited space in the overcrowded operating theater. Because of the relatively low operational cost, this diode laser may become a cost-effective device even in low-volume stapes surgery clinics.

Acknowledgments: The authors thank the Atos Medical BV for providing the laser equipment used during this study.

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