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ABSTRACT

The outcome of stapedotomy depends on several surgical steps. Using laser light, the ossicular chain can be handled and the oval window can be punctured with a non-touch method. Various lasers are being used or considered, however, it is not clear which settings and characteristics will contribute to optimal or adverse effects (vestibule damage and loss hearing frequencies). Using a unique high speed thermal imaging setup based on Schlieren techniques, the mechanical and thermal effects during laser stapedotomy were studied in an inner ear model consisting of human, fresh frozen stapes positioned on a liquid filled cavity in a gel cast. The cw KTP (532 nm), cw CO2 (10.6 µm), cw Thulium (2.0 µm), pulsed Er,Cr:YSGG (2.78 µm) coupled to special fiber delivery systems were applied at typical clinical settings for comparison. The imaging techniques provided a good insight in the extent of heat conduction beneath the footplate and (explosive) vapour formation on both sides. For the pulsed laser modes, explosive vapour expansion can to be controlled with optimized pulse energies while for continuous wave lasers the thermal effects can be controlled with the pulse length and repetition rate. The fluence at the tip of the delivery system and the distance to the footplate has a major impact on the ablation effect. The pulsed IR lasers with fiber delivery show to be promising for a controlled stapedotomy.

Keywords: Stapedotomy, KTP laser, Thulium laser, CO2 laser, Er,Cr:YSGG laser, High Speed Imaging, thermal imaging

1. INTRODUCTION

1.1 Stapedotomy techniques

Stapedotomy is a procedure to improve hearing in patients with otosclerosis. It was introduced as early as the end of the 19th century and many improvements to the technique have been proposed [1]. The most important part of the procedure is the perforation of the stapes footplate, traditionally done by a skeeter drill or a micro-pick instrument. Possible risks of this direct-contact method, generating substantial mechanical energy, include sensorineural hearing loss, vertigo and facial nerve paralysis. A non-contact method to perforate the footplate is preferable to minimize these risks. First non-contact technique was described by Perkins in 1980, using an Argon laser to make a precise hole in the footplate [2]. Up to now, various lasers have been proposed for this cause; however, each has its own characteristics, with the possibility to inflict harm to the inner ear.

1.2 Currently used lasers

Classically used lasers as Argon (488 nm) and KTP (532 nm), bear the risk of damaging the inner ear, due to their light transmission through the perilymph, causing residual energy to be absorbed at the pigmented area of the neuro-endothelium of the vestibule. The pulsed Er:YAG laser (2.78 µm) has the advantage of its high absorption in bone, leaving minimal residual energy to enter the vestibule. Nonetheless, the explosive ablation of the bone causes a sound pressure wave, which is considered traumatic to inner ear hear cells, with potential sensorineural hearing loss and vertigo as a result [3]. The CO2 laser (10.6 µm) is well absorbed in both fluid and bone, causing a precise perforation, with the excess of energy being highly absorbed by the perilymph, generating heat [4]. Although this heat is potentially damaging, the largest disadvantage was the absence a fiber delivery system. Using a micromanipulator coupled to the
operating microscope, the beam was focused through the hearing channel onto the footplate. Potentially, the beam could miss the footplate and harming surrounding structures as the facial nerve.

1.3 Recent developments

Recent developments include the introduction of new lasers to the field. The continuous wave Thulium laser (2 µm) and pulsed Er,Cr:YSGG (2.78 µm). Both have the advantage of high absorption in water and bone. In contrast to the Er:YAG, the Er,Cr:YSGG has the possibility of longer pulse time, which results in a more gradual ablation of footplate, without the explosions known with the Er:YAG. Also progress was made in fiber delivery systems, the CO2 can now be delivered by a hollow-wave guide, making the laser beam more accurately delivered to the foot plate.

The aim of this study is to visualize the thermal and mechanical effects of these lasers in an inner ear model with high speed imaging. The optimal laser would inflict minimal temperature increase in the middle ear and would prevent debris, bubble or air formation in the inner ear. Mechanical effects causing turbulence in the inner ear of shockwave should be minimal.

2. METHODS

2.1 High Speed Imaging techniques

To study the mechanical effects, a high speed camera (Fastcam MC1, Photron, San Diego, Ca, USA) with close-up optics was used. The use of lasers in stapedotomy can induce explosive water vaporization resulting in bubble formation in the vestibule and scattering of particles. These effects evolve in the sub millisecond region and can be easily missed when recorded with conventional cameras. The high speed camera recorded effects with a frame-rate up to 2000 frames per second (500 µs resolution). As KTP wavelength is visible, a filter (endoscope filter, #10-0721, OD 5, Laserscope, San Jose, Ca, USA) was used to block the 532 nm wavelength to protect the camera from the intense light flashes.

2.2 High speed thermal imaging using Color Schlieren Techniques

To study the thermal effects, a special optical technique was used based on color Schlieren imaging [5]. This technique visualizes non-uniformities in the refractive index of a transparent medium induced by e.g. a temperature gradient. Light rays passing through a transparent tissue phantom will be deflected if a temperature gradient, caused by laser induced heating, is present. The non-deflected and deflected rays are focused onto a rainbow filter by an imaging lens (figure 1). This produces a color ‘thermal’ image showing the presence and dynamics of the temperature gradient in real time (inset fig.1). With a high intensity white illumination source, frame rate up to 500 f/s (= 2 ms resolution) could be obtained.

![Figure 1. Scheme of the color Schlieren imaging setup. The inset shows an example of a temperature gradient inside a phantom tissue with a laser induced vapor bubble on the surface.](image-url)
2.3 Inner ear model

To visualize effects in the vestibule during perforation of the footplate, experiments were performed on an inner ear model (figure 2). This inner ear model consisted of a slab of transparent polyacrylamide gel sandwiched between 2 glass windows. A 3 mm deep artificial vestibule was created in the gel, corresponding to the depth of a human vestibule. It was filled with NaCl 0.9%, mimicking the perilymph. A small strip of dialysis membrane was placed over the vestibule, with a small hole centrally. A stapes footplate (fresh frozen human cadaver) was placed on top of the hole, so the footplate would make direct contact with the fluid, without sinking. The model was placed in the imaging set-up. The footplate was exposed to the different lasers either with a fiber tip placed directly on the footplate or at 1 mm above. As the KTP wavelength is not absorbed by fluid but by pigmented areas in contrast to the other laser wavelengths used, the polyacrylamide gel was dyed with cherry red colour pigment to mimic absorption effects in the wall of the vestibule.

![Figure 2. Inner ear model. Left: schematic setup. Right: actual image of model with a stapes resting on a membrane above the vestibule](image)

2.4 Laser systems

The experiments were performed comparing the following laser systems at settings which are typically used in the clinic as published in literature (see table 1).

- **KTP laser**: A 532 nm KTP laser (IDAS, Quantel Derma, Erlangen, Germany) was used coupled into a fiber handpiece (Endo-ENT, Biolitec, 200 micron).
- **Thulium laser**: A 2 µm continuous wave (‘Thulium’) laser was used coupled to a 365 µm fiber.
- **CO₂ Laser**: A 10.6 µm continuous wave CO₂ laser (A.R.C. laser, Nurnberg, Germany) was used. The light was delivered by a 3rd generation Omniguide Hollow Wave Guide (Beam-Path OTO-S, 250 µm, Omniguide, Cambridge, MA, USA). A flow with Helium gas was delivered through the center of the fiber (> 1 bar) to prevent pollution of the fiber core.
- **Er,Cr:YSGG laser**: A 2.78 µm Er,Cr:YSGG laser (Waterlase MD, Biolase, Irvine, Ca, USA) was used coupled to a 300 µm fiber tip.

<table>
<thead>
<tr>
<th>Laser</th>
<th>Energy Output (mJ)</th>
<th>Pulse Time (ms, µs)</th>
<th>Spot Size (µm)</th>
<th>Fluency (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTP</td>
<td>100 mJ (at 1 W)</td>
<td>100 ms</td>
<td>200</td>
<td>318</td>
</tr>
<tr>
<td>Thulium</td>
<td>600 mJ (at 6 W)</td>
<td>100 ms</td>
<td>365</td>
<td>573</td>
</tr>
<tr>
<td>CO₂</td>
<td>200 mJ (at 2 W)</td>
<td>100 ms</td>
<td>250</td>
<td>407</td>
</tr>
<tr>
<td>Er,Cr:YSGG</td>
<td>150 mJ (6 x 25 mJ)</td>
<td>60 and 600 µs</td>
<td>300</td>
<td>212</td>
</tr>
</tbody>
</table>

*Table 1: Settings shown by energy output (mJ), pulse time (ms, µs), spot size (µm) and fluency (J/cm²)*
3. EXPERIMENTS

The mechanical and thermal effects of the various lasers systems were studied in the inner ear model in figure 2 using the lasers at the settings presented in table 1. The laser ablation process of drilling a hole in the stapes was recorded which the high speed imaging technique at 2000 f/s and with the thermal imaging technique at 500 f/s. For each laser setting 2 to 3 holes were drilled in the stapes to confirm reproducibility of the observed effects. The holes were photographed through a microscope and evaluated on shape and presence of carbonization. The video clips were examine by the authors and scored on criteria as presence of debris, bubbles, air and temperature increase and turbulence in the fluid of the vestibule.

4. RESULTS

4.1 KTP laser

High speed imaging showed white light flashes in the stapes with smoke arising from the hole (figure 3). The thermal imaging showed a small zone of heated fluid underneath the stapes after perforation. There was no heating of the far wall of the vestibule from the beam transmitted through the liquid after perforation. The holes showed substantial carbonisation along the wall.

![Figure 3. KTP laser.](image1.png)

*Left: high speed imaging, with some particles ejected from the hole and light effects in the stapes.*  
*Right: thermal imaging, some heat effects just below the surface, none in the vestibule wall.*

4.2 Thulium laser

High speed imaging showed vapor formation and ejection of particles at high velocity above the footplate coming from the hole. The thermal imaging showed cyclic heating of the fluid just beneath the footplate (figure 4). The holes created showed substantial carbonization and irregular hole without a large opening.
5.3 CO₂ laser with hollow wave guide delivery

The CO₂ laser light was delivered through a hollow wave guide with the tip positioned ~1 mm above the footplate. High speed imaging showed light flashes and ejection of particles from the footplate during perforating. After perforation energy is absorbed in the fluid of vestibule creating a stream of small bubbles (figure 5). Thermal imaging showed a stream of heated liquid surrounding the vapor bubbles in the vestibule. The holes showed carbonization along the wall.
5.4 Er, Cr: YSGG laser

High speed imaging showed explosive vapor formation first above and later underneath the footplate during a series of 6 pulses. The bubble inside the vestibule collapses instantly and induces turbulence in the fluid up to the bottom of the vestibule. Thermal imaging showed minimal thermal effects attributed to a fast dissipation through the fluid by the turbulence of the imploding bubble (figure 6). The ‘long’ 600 µs pulse creates holes with carbonisation at the wall (figure 7). When the fiber was in contact, the hole is cylindrical (size of opening at top and bottom is equal). When the fiber was at 1-2 mm above the footplate, the hole is tapered. The ‘ultra short’ 60 µs is the only laser creating a cylindrical hole without carbonisation of the borders (figure 7).

![Figure 6: Er, Cr: YSGG laser](image1)
*Left: High speed imaging, the bubbles and fluid turbulence wave in vestibule
Right: thermal imaging, minimal thermal effect can be observed.*

![Figure 7: Er, Cr: YSGG laser ablated holes in footplate](image2)
1. 600 µs pulse none-contact, 2. 600 µs pulse in-contact, 3. 60 µs pulse in-contact
5.5 Comparison between lasers

A summary of the results is presented shown in table 2 which a scoring for the optimal and adverse effect

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KTP</th>
<th>Th</th>
<th>CO₂</th>
<th>YSGG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical shaped hole</td>
<td>0</td>
<td>--</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Minimal carbonisation of wall side</td>
<td>~~</td>
<td>~~</td>
<td>~~</td>
<td>+</td>
</tr>
<tr>
<td>Minimal temperature increase of fluid in inner ear</td>
<td>0</td>
<td>--</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Debris and bubble/air formation in inner ear</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>No laser light on far wall of inner ear</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Minimal mechanical effect, turbulence in inner ear</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>Mechanical shock in inner ear</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>~~~</td>
</tr>
</tbody>
</table>

Table 2: comparison between lasers. Legend: + optimal, --adverse, ~less optimal?, 0 neutral

5. DISCUSSION

Our data clearly confirm that there are significant differences in mechanical and thermal effects of the various lasers systems used. These effects can be relevant to ensure good postoperative results. Damage to the inner ear can result in decreased hearing levels, vertigo and tinnitus. Decrease in hearing levels (>15dB) up to 17% of the patients in the first postoperative days have been described for Er:YAG laser. The same study shows transient tinnitus and vertigo in one third of patient population [4]. Fortunately, most of these adverse effects are transient, but in some patients they remained. Randomized controlled trials between lasers to compare adverse effects are lacking. A recent non-randomized trial comparing KTP versus CO₂ laser in stapedectomy shows slightly better hearing results with CO₂ laser [6]. Comparing all different lasers in clinical setting with the many variables as pulse time, fluence etc. would time consuming. Therefore, a better approach seems to study the characteristics of the mechanical and thermal effects in a controlled laboratory setting using visualization techniques.

We created an inner ear model, mimicking the human inner ear. The model needed to be transparent, to make visualization possible. We choose to use fresh frozen human stapes, as stapes fixed in formaldehyde become dehydrated, causing changes in ablation effect. The model makes visualization of dynamics of thermal effects possible using the color Schlieren technique [5]. This is not a quantitative measurement, but makes comparison between lasers possible. High Speed imaging visualizes explosive vapor formation, particle ejection and bubble formation in the vestibule. These image modality helps us to obtain a better understanding what happens in the inner ear when performing a stapedotomy. In both imaging techniques variation is possible between experiments. Also individual interpretation of data may vary. We conducted each experiment a minimum of three times to ensure reproducible results. To minimize individual interpretation, multiple investigators looked at the footage independently.

Comparing results, the KTP laser makes a small hole with carbonization at the borders, with minimal thermal and mechanical effects. The intense light flashes of the visible 532 nm wavelength can be disturbing for the surgeon. The Thulium laser only perforates when the fiber tip is in direct contact with the footplate. Extensive effects in heating and particle formation are observed. A large brittle area of carbonization is created; sometimes it is difficult to identify the actual hole. This might introduce potential adverse effects in clinical settings. If the surgeon, when in doubt, hits the same spot again, large vapor bubbles can form in the vestibule. The CO₂ laser is delivered to the footplate using a hollow wave guide. A hole is created without direct contact to the footplate, with relative little heat generation. Small particles and bubbles enter the vestibule after perforation. The clinical effects of these findings are not known, but one might argue it could be damaging to inner ear function. The Er,Cr:YSGG laser is being used in dentistry and is fairly new in the ENT field. In contrast to the Er:YAG laser, it can be fiber delivered and the pulse length can be extended to 600 µs which gives less explosive effects and potentially less shock waves. This might increase for the shorter pulse mode of 60 µs however the perforated holes are perfectly cylindrical and without any carbonisation.
Comparing of these lasers systems more research is needed to obtain a better quantification by e.g. sound and pressure measurements or thermal imaging. The effects of direct contact of the fiber, versus non contact of the fiber should be further investigated. Other new lasers systems with specialized fiber tips should also be considered.

6. CONCLUSIONS

To study the mechanism of stapedotomy, high speed and thermal imaging techniques provided a good insight in the extent of heat dissipation beneath the footplate, (explosive) vapour formation and particle ejection. The fluence at the footplate and the distance to the footplate have a major impact on the ablation effect. The pulsed IR lasers with fiber delivery show to be promising for a controlled stapedotomy.

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REFERENCE LIST