Lasers Med Sci (2003) 18: 154–161
DOI 10.1007/s10103-003-0274-6

ORIGINAL ARTICLE

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# Transmeatal cochlear laser (TCL) treatment of cochlear dysfunction: A feasibility study for chronic tinnitus

Received: 31 July 2003 / Accepted: 13 August 2003

**Abstract** Low-level-laser-therapy (LLLT) targeting the inner ear has been discussed as a therapeutic procedure for cochlear dysfunction such as chronic cochlear tinnitus or sensorineural hearing loss. Former studies demonstrate dose-dependent biological and physiological effects of LLLT such as enhanced recovery of peripheral nerve injuries, which could be of therapeutic interest in cochlear dysfunction. To date, in patients with chronic tinnitus mastoidal and transmeatal irradiation has been performed without systematic dosimetric assessment. However, light-dosimetric studies on human temporal bones demonstrated that controlled application of laserlight to the human cochlea depends on defined radiator position within the external auditory meatus. This feasibility study first presents a laser application system enabling dose-controlled transmeatal cochlear laser-irradiation (TCL), as well as preliminary clinical results in patients with chronic cochlear tinnitus. The novel laser TCL-system, consisting of four diode lasers ($\lambda = 635$ nm–830 nm) and a new specific head-set applicator, was developed on the basis of dosimetric data from a former light-dosimetric study. In a preliminary clinical study, the TCL-system was applied to 35 patients with chronic tinnitus and sensorineural hearing loss. The chronic symptoms persisted after standard therapeutic procedures for at least six months, while retrocochlear or middle-ear pathologies have been ruled out. The patients were randomised and received five single diode laser treatments ($\lambda = 635$ nm, 7.8 mW cw, n = 17 and $\lambda = 830$ nm, 20 mW cw, n = 18) with a space irradiation of 4 J/cm$^2$ site of maximal cochlear injury. For evaluation of laser-induced effects complete otolaryngologic examinations with audiometry, tinnitus masking and matching, and a tinnitus-self-assessment were performed before, during and after the laser-irradiation.

The first clinical use of the TCL-system has been well tolerated without side-effects and produced no observable damage to the external, middle or inner ear. Changes of tinnitus loudness and tinnitus matching have been described. After a follow-up period of six months tinnitus loudness was attenuated in 13 of 35 irradiated patients, while two of 35 patients reported their tinnitus as totally absent. Hearing threshold levels and middle ear function remained unchanged. Further investigations by large double-blind placebo-controlled studies are mandatory for clinical evaluation of the presented TCL-system and its therapeutic effectiveness in acute and chronic cochlear dysfunction.

**Keywords** Human cochlea · Light-dosimetry · Low-level-laser-therapy · Sensorineural hearing loss · Tinnitus · Transmeatal laser treatment

## Introduction

The therapeutic effectiveness of low-level-laser-therapy (LLLT) or low-intensity laser irradiation for different medical applications has been documented, but is still controversial. Beneficial clinical treatment has been reported for healing of wounds, tissue repair, musculoskeletal complications and pain control [1–4]. Low-intensity laser irradiation increases cell proliferation [5], synthesis of ATP [6] and collagen [7], and the release of growth factors [8, 9]. In contrast to the majority of

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investigations, some results did not provide convincing evidence for the clinical potential of low-intensity laser irradiation, such as failure to demonstrate hypoalgesic effects or stimulatory effects on collagen synthesis [10, 11]. LLLT has also been controversially discussed for repair mechanisms in injured nerves [12–17]. However, beneficial effects on neuronal tissues were predominant, since most studies revealed that LLLT prevents neuronal degeneration, promotes improved neuronal (electrophysiological) function and repair, and enhances neural growth [12, 14–18]. Different studies for LLLT focused on the determination and the modulation of irradiation parameters that seem to play a pivotal role for its effectiveness: The biological effects of low-level-laser-therapy are supposed to depend largely on well-controlled parameters, e.g. wavelength ($\lambda =$ 630 nm–904 nm), waveform (cw, pulsed, Q-switched), power (10–90 mW), dosage per site (1–10 J/cm$^2$), duration of irradiation, type of irradiated cell, and time interval between injury and irradiation [1, 12, 15–17, 19–21].

During the last decade, the widespread clinical application of low energy laser photostimulation included several studies on therapy of chronic tinnitus aurium and sensorineural hearing loss (Table 1). Therapeutic success rates were controversial and are still matter of discussion. Significant reduction of tinnitus intensity was reported by different authors in a range of 15% of patients, up to 67% of patients [22–24, 27], whereas in other studies the relief of tinnitus by laser-irradiation was supposed to be placebo-induced too [25–29]. Only Wilden described improvement of hearing threshold shifts in more than 80% of patients [24, 30], while the other studies dealing with low-level-laser-therapy of the inner ear did not observe significant changes in auditory threshold [22, 23, 25–29]. The comparison of therapeutic outcome rates among all those studies is difficult, because differences in technical parameters, targets of irradiation, treatment schedules and study design are obvious (Table 1). In earlier studies, a combined helium-neon ($\lambda = 632$ nm) and gallium-arsenide laser ($\lambda = 904$ nm) beam was directed to the mastoid, accompanied with intravenous application of ginkgo biloba extracts [22, 23, 26, 29]. Later on, the irradiation technique was modified by targeting the external auditory meatus with infrared lasers ($\lambda = 830$ nm) [24, 25, 27]. Even though the authors expected to achieve effective light dosages within the injured cochlea by this modification [27], a recent prospective double-blind study demonstrated failure of tinnitus attenuation by transmeatal low-power laser irradiation with similar irradiation parameters [25].

Besides various study designs and the complicated pathophysiology of inner ear disorders, it has to be considered that different degrees of laser light transmission to the human cochlea could have caused therapeutic outcome differences. This fact is even more important, since in none of the previous studies a certain dosage of laserlight has been defined for the target of irradiation, whether it was the mastoid, the cochlea or

**Table 1** Previous clinical studies of low-level-laser treatment for patients with chronic tinnitus

| Author | Year | Laser type and $\lambda$ [nm] | Power [mW] and waveform | [min] × frequency of treatments | Target of irradiation | Dosimetric Study | Study design | Ginkgo i.v. | Patients (n) | Tinnitus relief (%) of patients |
|---|---|---|---|---|---|---|---|---|---|---|
| Partheniadis | 1993 | He-Ne 632<br>Ga-Al-As 904 | 12 cW 9-20 p | 10 × 12 | mastoid | no | treatment study | yes | 28 | 15 |
| Olivier | 1993 | He-Ne 632<br>Ga-Al-As 904 | 12 cW 30 p | 8 × 8 | mastoid | no | single-blind | yes | 40 | 50 * |
| Wedel | 1995 | He-Ne 632<br>Ga-Al-As 904 | 12 cW 9–20 p | 10 × 12 | mastoid | (yes) | single-blind | yes | 155 | 6–16 |
| Plath | 1995 | He-Ne 632<br>Ga-Al-As 904 | 12 cW 30 p | 8 × 8 | mastoid | no | single-blind | yes | 40 | 15–45 * |
| Wilden | 1996 | He-Ne 632<br>Diode 830 | 20 cW 30–100 p | 30 × 15 | mastoid eam | no | treatment study | yes | 139 | 67 * |
| Shiomi | 1997 | Diode 830 | 40 cW | 9 × 10 | eam | no | treatment study | no | 38 | 26–60 * |
| Mirz | 1999 | Ga-Al-As 830 | 50 cW | 10 × 15 | eam | no | double-blind | no | 50 | 18 |

cW: continuous wave; p: pulsating; eam: external auditory meatus; *: significant treatment outcome (according to the authors) the temporal bone at all. LLLT is known to depend upon irradiation parameters demanding light-dosimetry for the target [1, 12, 20, 21], which in this case even represents complex anatomic features of the human cochlea.

Recently, light-dosimetric assessment of the human cochlea has been performed and it has been defined as the prerequisite for application of laserlight to the inner ear [31]. Based upon this dosimetric data, we have developed a laser-system that enables controlled transmeatal cochlear laser irradiation (TCL) for clinical trials. This study presents the new low-power laser device and its first clinical assessment for regeneration of inner ear disorders. First of all, a preliminary prospective investigation in 35 patients suffering from chronic tinnitus and sensorineural hearing loss was performed.

## Materials and methods

### Laser irradiation source with head-set applicator

A laser-irradiation source was developed and was built up for clinical application of low-level laserlight to the human cochlea (Fig. 1). The laser unit was equipped with four different diode lasers delivering continuous wave (cw) laserlight (wavelength $\lambda = 635$ nm, power maximum $p = 15$ mW; $\lambda = 690$ nm, $p = 30$ mW; $\lambda = 780$ nm, $p = 50$ mW; $\lambda = 830$ nm, $p = 50$ mW; Laser 2000, FRG). The power of each laser could be adjusted and was measured by an integrated power meter. The laser of choice was activated and deactivated by a timer enabling irradiation for a predefined time period in seconds (Conrad electronics, Munich, FRG). The laserlight was applied to the external auditory meatus by a microlens fibre delivering a flat homogeneously illuminated circular irradiation field (400 μm fibre, cone angle = 31.8°, NA = 0.37; AOC Medical Systems, South Plainfield, NJ, USA). The microlens fibre was connected to and immobilised by a recently developed head-set, consisting of a synthetic headband-construction (3 cm width, 2.5 mm thickness) that could be adjusted and fastened to the upper head of the patient (Fig. 2). At the lateral site of the head-set a metal fastening rail was attached and could be equipped with a hydraulic micro-tripod with three different micro-joints enabling movements in three-dimensional directions (Hoffmann, Munich, FRG). The tripod could be immobilised in each defined position by a hydraulic mechanism. An ear speculum was attached to the distal end of the tripod and could be variably positioned within the external auditory meatus under microscopic control. The microlens fibre was attached to a screwing support device and could be moved towards the tympanic membrane and positioned in a certain angle in relation to the tympanic membrane, while the tympanic membrane was controlled under the microscope. The microlens fibre was positioned within the external auditory meatus for illumination of the tympanic membrane according to the defined localisation by previous lightdosimetric experiments [31] and immobilised by the screw device (Fig. 2).

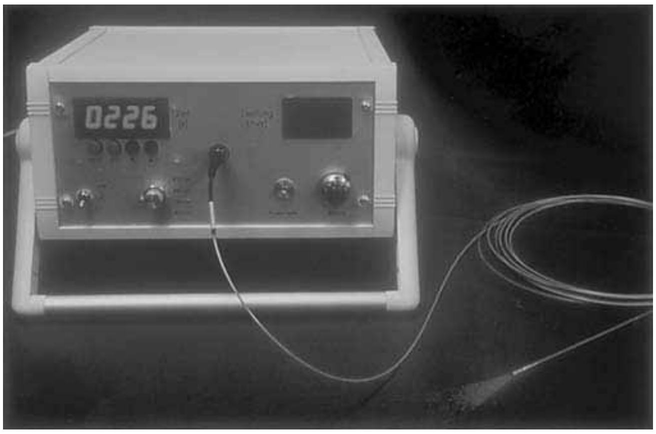

**Fig. 1** The new-developed TCL-system with four different diode lasers ($\lambda = 635$ nm-830 nm) and integrated power meter. The laserlight is delivered in the centre of the laser unit through the attached microlens laser fibre. The irradiation is activated by a timer

### Clinical application study: patients and otologic examinations

The study included 35 patients (mean age 46 ± 12, m:f = 1.4:1), suffering from chronic permanent one-sided tinnitus of more than six months with or without sensorineural hearing loss. The tinnitus even persisted for several months after treatment with intravenous dextran/pentoxifyllin or hydroxyethyl starch (HES)-pentoxifyllin infusions (ten infusions of each 500 ml dextran or HES) combined with intravenous corticoids (250 mg solu-Decortin H/day and reduction of 25 mg/day). In all patients, retrocochlear and central nervous system abnormalities have been ruled out by audiometric assessment with central auditory tests, cranial high resolution CT-scans or magnetic resonance imaging of the brain. Vestibular disorders were excluded before and after laser treatment by electronystagmography including recording for spontaneous, positional, optokinetic and artificially induced caloric nystagmus. Audiometric assessment in each patient concerned tuning fork testing, pure-tone audiometry, speech audiometry, tinnitus masking and pitch and loudness matching according to Feldmann, impedance audiometry, distortion product otoacustic emissions (DPOAE) and brainstem electric response audiometry (BERA). Tinnitus was classified as improved or attenuated, when reduction of tinnitus loudness match was at least 10 dB, provided that tinnitus pitch match (kHz) remained unchanged. Moreover, marked changes in tinnitus pitch match known to be associated with subjective relief of tinnitus were considered for evaluation of therapeutic outcome, too.

In addition, the therapeutic outcome concerning the degree of tinnitus was quantified by self-assessment on defined visual

**Fig. 2** The new-developed head-set applicator for the TCL-system. A synthetic headband-construction is adjusted and fastened to the upper head of the patient. The microlens laser fibre is positioned within the external auditory meatus nearby the tympanic membrane (in defined position) and is immobilised by a micro-tripod with ear speculum at the lateral site

analogue scales (VAS). The patients were asked to quantify the degree of tinnitus by different evaluation factors, such as the severity and perceived loudness of tinnitus, the perceived frequency of tinnitus, the degree of attention paid to their tinnitus, and the annoyance associated with tinnitus. The VAS consisted of 20 cm lines with endpoints denoted by the words ‘total absence’ and ‘maximum’ of tinnitus loudness. The pretherapeutic degree of tinnitus was defined at a degree of ten on the VAS for each patient (baseline). Total absence of tinnitus was defined as a degree of zero, values between zero and ten were corresponding to mild (7 to 9), moderate (4 to 6), and strong (1 to 3) attenuation of tinnitus. Increase of tinnitus was correlated with values greater than ten (Figs. 3 and 4).

Audiometric assessment, self-assessment, microscopic examination of the external auditory meatus and tympanic membrane were performed before, during (days 1, 3, 5, 8, 10, 12, 15) and after (1 week, 4 weeks, 3–6 months) laser treatment. All patients were asked to observe and describe any minor or major side-effects during and after laser treatment. Before examination procedures, the patients were randomised between both treatment groups (wavelengths $\lambda = 635$ nm or $\lambda = 830$ nm).

## Laser irradiation

Patients were irradiated according to a defined treatment protocol (five days/times during a two-week treatment period) with the novel TCL-device. In this preliminary study two different diode lasers (out of the four lasers in the laser-source) at $\lambda = 635$ nm ($n = 17$) and $\lambda = 830$ nm ($n = 18$) were applied. Irradiation was performed with a biostimulatory dose of 4 J/cm$^2$ space irradiation at the cochlear area of the supposed maximum of cochlear injury (localisation of maximum auditory threshold shift and/or tinnitus matching frequency).

In our previous study, the mandatory data of light transmission to the human temporal bone has been defined and well documented ex vivo [31]. The necessary light dose, which had to be applied to the tympanic membrane in order to achieve the 4 J/cm$^2$ space irradiation, was first calculated from the values of light transmission across the tympanic membrane and the promontorium to the defined cochlear target area. The applied light dose to the cochlear hair cells of the patients was identical to any direct irradiation of cells in culture and mimicking a dose of 4 J/cm$^2$ of collimated light. Figure 5 demonstrates the laser light dose [J] delivered on the tympanic membrane (of the patients) with a microlens fibre at a distance of 1.5 cm to the umbo of the tympanic membrane. This way, transmeatal cochlear laser irradiation (TCL) with different wavelengths ($\lambda = 635$ nm–830 nm) was performed in order to achieve a biostimulatory dose of 4 J/cm$^2$ space irradiation at the cochlear area of maximum cochlear injury (Fig. 5). The cochlear light dose was dependent upon the cochlear angle (0°–900°) and the corresponding acoustic frequency (100–10000 Hz), respectively. The wave-shaped light doses were caused by variation of light transmission through the middle-ear and the promontorium to the

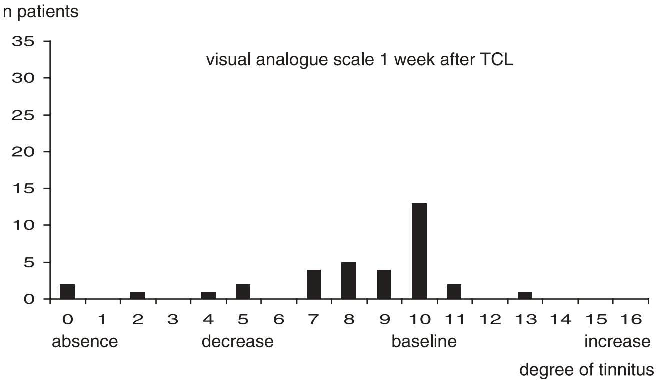

**Fig. 3** Visual analogue scale (VAS) for tinnitus assessment one week after completion of transmeatal cochlear laser irradiation (TCL). Baseline tinnitus was defined at a degree of 10 before TCL and represents unchanged tinnitus after TCL (x-axis)

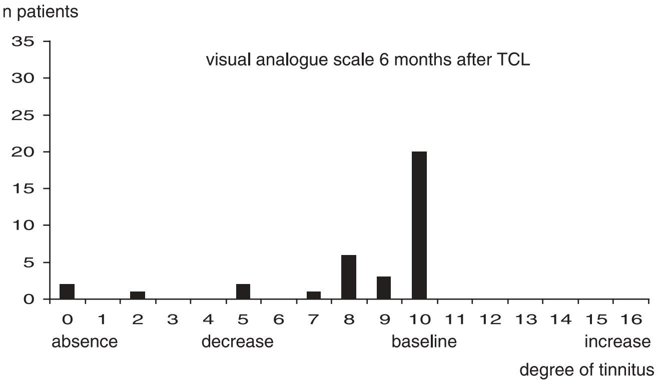

**Fig. 4** Visual analogue scale (VAS) for tinnitus assessment six months after completion of transmeatal cochlear laser irradiation (TCL). Baseline tinnitus was defined at a degree of 10 before TCL and represents unchanged tinnitus after TCL (x-axis)

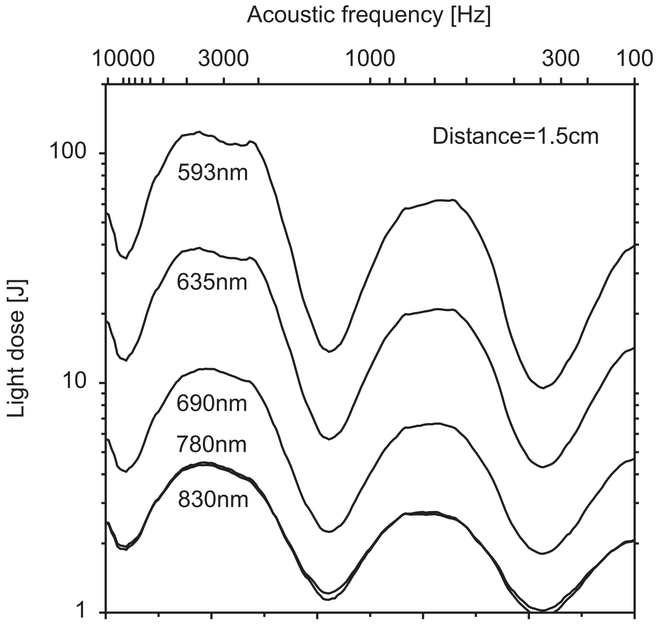

**Fig. 5** Laser light dose [J] that has to be applied to the tympanic membrane in order to achieve a biostimulatory dose of 4 J/cm$^2$ space irradiation at the cochlear area of maximum cochlear injury. Transmeatal cochlear laser irradiation (TCL) with different wavelengths ($\lambda = 635$ nm–830 nm) is performed with a microlens fibre at a distance of 1.5 cm to the umbo of the tympanic membrane. The light dose [J] is dependent upon the cochlear angle (0°–900°) and the corresponding acoustic frequency (100–10000 Hz), respectively. The wave-shaped light doses are caused by variation of light transmission through the middle-ear and the promontorium to the cochlea. Note light dose minima at acoustic frequencies of about 8000, 1500 and 400 Hz. Data given are means

cochlea, according to the lightdosimetric data of the previous study [31]. Light dose minima can be recognised at acoustic frequencies of about 8000, 1500 and 400 Hz (Fig. 5).

According to the different light transmission, the regions of the cochlear windings will be irradiated with certain ranges of space irradiation (0,4 to 40 J/cm$^2$ for $\lambda = 635$ nm and 1,0 to 16 J/cm$^2$ for $\lambda = 830$ nm). The laser source was then adjusted to the defined parameters wavelength and time of irradiation at maximum laser power. The head-set was attached to the patient with positioning of the microlens fibre within the external auditory meatus under microscopic control. The tip of the laser fibre was localised in the centre of the external auditory meatus at a distance of 1.5 cm from the umbo of the tympanic membrane according to light-dosimetric data of the human cochlea [31]. The laser was activated and deactivated by the timer.

## Results

### Laser irradiation source with head-set applicator

The first clinical usage of the developed laser unit and head-set applicator for TCL was without any major or minor technical problems. The laser-source worked regularly with stable power emission measured by the integrated power meter and controlled by an external power meter. The head-set applicator allowed in all patients exact and firmly immobilised central positioning of the microlens fibre within the external auditory meatus. The laser device was suitable and well-designed for patient treatment, since movements of the patient's head and neck were tolerated and the laser fibre was not impaired keeping permanently the exact position within the auditory meatus.

### Clinical application study

The laser treatment procedures were performed in all patients without major complications or side-effects. The transmeatal low-level-laser-irradiation was generally well tolerated by all patients, only some patients described temporarily mild irritation or itching of the external auditory meatus during the treatment. In all patients any inflammatory, thermical or reactive changes within the irradiated external auditory meatus following laser exposure have been ruled out by microscopic examination. The patients completely followed and finished up the defined treatment procedures of five laser-irradiations. Pretherapeutic and posttherapeutic vestibular tests were regular without any pathologies in all patients. In comparison to pretherapeutic audiometric assessment the pretherapeutic hearing impairment remained unchanged and there were no significant changes of hearing threshold levels, DPOAE's, tympanometries and impedance audiometries during and after laser-irradiation in all patients.

The degree of tinnitus could be quantified concerning loudness and frequency of tinnitus, the degree of attention paid to tinnitus, and the annoyance associated with tinnitus by self-assessment on VAS. After completion of laser-irradiation (on day 15), 12 (34%) patients described tinnitus as unchanged, while 18 (51%) patients reported decrease of tinnitus (mild, moderate, strong), and in two (6%) patients tinnitus was totally absent. In three (9%) patients tinnitus was slightly increased (Table 2). One week after completion of laser treatments, in 13 (37%) patients tinnitus remained unchanged by self-assessment, while 17 (49%) patients reported attenuation of tinnitus of the irradiated ear, and in two (6%) patients tinnitus was absent. In three (9%) patients tinnitus was still increased (Table 2, Fig. 3). During follow-up after six months, tinnitus remained unchanged in 20 (57%) patients, while 13 (37%) patients described a decrease of their ear ringing, and in two (6%) cases tinnitus was still not present (Table 2, Fig. 4). None of the patients described changes of perceived tinnitus frequency on visual analogue scales during laser-treatment until follow-up for six months (Table 2).

Those results were partially confirmed by audiometric changes of tinnitus masking and pitch and loudness match: After completion of laser-irradiation tinnitus was improved in 13 (37%) patients including attenuation (nine patients, 26%) and modulated frequency (four patients, 11%). In 18 (51%) cases tinnitus was assessed as unchanged. Increase of tinnitus was found in two (6%) patients and during the one week follow-up, five (14%) patients suffered from enhanced tinnitus. After six months, in 20 (57%) patients tinnitus remained unchanged, while a significant improvement of tinnitus loudness was observed in nine (26%) patients and in another four (11%) patients a significant modulation of tinnitus frequency with changed tinnitus masking was detected. In two (6%) patients, tinnitus was still totally absent. There was no further increase of tinnitus four weeks after completion (Table 2).

**Table 2** Assessment of tinnitus degree in transmeatal cochlear laser treatment (TCL)

| Assessment of tinnitus degree (n = 35) | Visual analogue scales | | | | Audiometric assessment | | | |
|---|---|---|---|---|---|---|---|---|
| | After laser treatment | 1 week follow-up | 4 weeks follow-up | 6 months follow-up | After laser treatment | 1 week follow-up | 4 weeks follow-up | 6 months follow-up |
| Attenuated | 18 | 17 | 15 | 13 | 9 | 8 | 9 | 9 |
| Modulated frequency | 0 | 0 | 0 | 0 | 4 | 4 | 4 | 4 |
| Disappeared | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Unchanged | 12 | 13 | 16 | 20 | 18 | 16 | 20 | 20 |
| Increased | 3 | 3 | 2 | 0 | 2 | 5 | 0 | 0 |

After laser treatment, on day 15 of laser treatment following last irradiation with TCL-system

All observed effects were similar in both treatment groups and were independent of the used wavelength of the laser ($\lambda = 635$ nm or $\lambda = 830$ nm), respectively.

## Discussion

Low-level-lasertherapy (LLLT) targeting the inner ear as a therapeutic device in cochlear dysfunction such as chronic cochlear tinnitus or sensorineural hearing loss is still matter of discussion. Low-intensity laser irradiation in specific parameters is a novel and useful tool for the treatment of peripheral and central nervous system injuries and disorders. The enhancement and acceleration of the functional and morphological recovery of severely injured nerve tissue could be of therapeutic interest in inner ear disorders [12, 14, 15–17], since axonal injuries and degenerative neuronal changes are supposed to be responsible for cochlear dysfunction too. Besides various pathophysiological mechanisms of inner ear diseases and different theories on the origin of tinnitus, the methodical differences in study design, treatment schedules and irradiation parameters could contribute to therapeutic outcome ranges of previous investigations dealing with LLLT of the inner ear [22–27, 29] (Table 1).

In contrast to methods from former studies we present, for the first time, a developed laser device permitting transmeatal light dose-controlled cochlear irradiation (TCL) and have discussed its clinical application in a feasibility study for patients with chronic tinnitus and sensorineural hearing loss. The laser application system was developed for defined irradiation of the cochlea according to parameters obtained in a recent experimental lightdosimetric study of human petrous bones [31]. It has been well documented that quantified irradiation of the cochlea has to be performed transmeatally by a microlens laser fibre in a defined position within the external auditory meatus. This mode of irradiation leads to a characteristic cochlear light distribution depending upon the tonotopic organisation of the cochlear windings (cochlear area functionally mediating the perception of certain acoustic frequencies). On the basis of the obtained light-dosimetric data, this new laser device permits laser-induced treatment of a defined anatomical localisation within the human cochlear winding by a pre-defined light-dose [31]. In contrast to our method, the authors of former studies for low-intensity laser treatment of tinnitus could merely define and quantify the dose applied to the inner ear across the mastoidal bone and the middle ear, respectively.

Moreover, the authors only supposed to irradiate the cochlea by both mastoidal irradiation and irradiation of the external auditory meatus [22–29]. Our former investigation demonstrated that mastoidal irradiation results in therapeutically insufficient cochlear light doses, whereas for transmeatal application the radiator position has to be defined [31]. Even the light-dosimetric-controlled irradiation with the developed new TCL-system has lead to a certain variation of cochlear space irradiation (Fig. 5). This fact is even more important, since to our knowledge the method of TCL, applied on the basis of light-dosimetric data, represents the most scientific quantitative method for controlled cochlear laser-irradiation at this time. The wave-shaped variation of space irradiation has to be taken in consideration for any calculation of cochlear laser treatment in the future. In our previous clinical study, patients were treated with 4 J/cm$^2$ space irradiation at the site of maximum cochlear injury. Accordingly, all regions of the entire cochlea have been irradiated with certain ranges of space irradiation (0,4 to 40 J/cm$^2$ for $\lambda = 635$ nm and 1,0 to 16 J/cm$^2$ for $\lambda = 830$ nm). Indeed, those ranges did not totally fulfil the requirements of the suggested dosages from 1–10 J/cm$^2$ for LLLT. However, due to the complex anatomical situation of the human temporal bone only transmeatal laser-irradiation is reasonable, even if this method of TCL results in the extended wave-shaped variation of transmitted light.

The first clinical use of the laser-unit with the developed head-set applicator has been well tolerated by all patients without complications or side-effects. Any visible pathological changes or thermical reactions of the skin at the external auditory meatus and the tympanic membrane of the irradiated ear were ruled out by microscopic examinations. There was no impairment of eustachian tube and middle ear function confirmed by tympanometry, impedance audiometry, and pure tone audiometry. The results of these clinical examinations ensure to some extent that in this study the applied parameters of laser-irradiation are without local side-effects according to non-thermical low-level-laser-therapy [1]. The clinical application of the developed TCL-system was appropriate and without major side-effects or complications. Irradiation was performed accurately with a calculated biostimulatory light dose of 4 J/cm$^2$ at the cochlear area of the supposed maximum cochlear injury. In contrast to former clinical studies of low-level-laser treatment for patients with chronic tinnitus, in this investigation, the cochlear light dose at site of injury was in the recommended range between 1–10 J/cm$^2$ for LLLT [1, 12, 20].

The clinical treatment of tinnitus and sensorineural hearing loss resulted in subjectively described tinnitus attenuation in 18 (51%) patients and tinnitus disappearance in two (5%) patients after completion of therapy. At six months follow-up 13 (37%) patients reported decrease of tinnitus intensity and in two (5%) patients tinnitus was still absent. Audiometric assessment of tinnitus revealed that laser-induced changements of tinnitus loudness were less effective: At six months follow-up 15 (42%) patients felt improvement of their tinnitus including attenuation of tinnitus loudness (nine patients), modulation of tinnitus frequency (four patients), or disappeared tinnitus (two patients). In general, these preliminary results are in concordance with therapeutic outcomes of the previous studies concerning tinnitus relief ranging between 15% and 67% of patients.

Former studies were strikingly controversial concerning therapeutic effectiveness of low-level-laser treatment for patients with chronic tinnitus. Investigations were difficult to compare, since study designs, targets and parameters of laser-irradiation, and treatment schedules were different [22–27, 29] (Table 1). In our study, hearing threshold levels remained unchanged and vestibular function was stable in both treatment groups during the entire period of follow-up. The observations made in this study agree with almost all previous studies of LLLT for cochlear dysfunction, in which hearing thresholds, DPOAE's, tympanometries and impedance audiometries remained unchanged and vestibular function was not impaired [22, 23, 25–27, 29]. In particular, the stable DPOAE's during and after laser-irradiation underlined the results of unchanged hearing threshold levels measured by pure tone and speech audiometry. In more than 80% of patients, the former study of Wilden et al. describes the improvement of hearing threshold levels in all hearing frequencies (0.125 kHz to 12 kHz) by laser-irradiation of the ear, but has still not been comprehensible to other authors and cannot be confirmed by our data [24, 30]. During our study, three patients suffered from mild increase of tinnitus intensity on visual analogue scale basis. However, increases were not persistent and were no more described six months after completion of laser-irradiation. The reason for these side-effects remains unclear and should be further examined by larger treatment groups.

In contrast to all previous studies concerning LLLT and inner ear disorders, we applied two single lasers with different wavelengths ($\lambda = 635$ nm, $\lambda = 830$ nm) systematically and dose-controlled to the human cochlea for the first time. Patients have been randomised between both treatment groups. However, there was no significant difference of laser-induced effects on the degree of tinnitus between both different wavelengths. With this preliminary data it cannot be definitely determined whether both wavelengths were even effective or laser irradiation was therapeutically effective at all. Other possible reasons leading to these results are that the number of patients was too small and/or the results were induced by placebo-like effects in both groups. It has to be further analysed, if there is a difference between both wavelengths in therapeutic effectiveness. In addition, other wavelengths between $\lambda = 630$–$904$ nm should be applied for clinical evaluation according to parameters of laser-biostimulation [1].

The preliminary results of the presented TCL-system could indicate possible therapeutic benefits for cochlear injury and should therefore be further evaluated. However, placebo-induced side-effects have not been ruled out. The previously described accelerated regeneration and decreased degeneration of injured neuronal structures by LLLT are of therapeutic interest and could be responsible for the observed effects by TCL. Randomised double-blind studies on TCL with a larger number of patients are mandatory to exclude any placebo-induced mechanisms and to evaluate the impact of TCL in acute and chronic cochlear disorders. Further modifications of the TCL-system are necessary for such placebo-controlled double-blind applications. The observed discrepancy between results of visual analogue scales and audiometric assessments with tinnitus masking and matching have to be analysed, too. If further experimental in-vivo and in-vitro studies confirm the dependency of photochemical cellular response on parameters of dose and irradiation, following clinical studies have to be performed with optimised study design and parameters for TCL. Transmeatal cochlear laser treatment could open up the possibility of providing protection, repair and regeneration of inner ear dysfunction. Futural development of photo-reactive substances mediating or even enhancing biostimulatory effects of LLLT could possibly increase the impact of local photoactivating therapy for the inner ear.

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