Quantum Electronics **30** (11) 1031 – 1033 (2000)

PACS numbers: 42.62.Be; 43.35.Sx; 42.55.Rz
DOI: 10.1070/QE2000v030n11ABEH001858

Optoacoustic monitoring of laser correction of the ear shape

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Abstract. Acoustic monitoring of a plastic operation for reshaping the porcine ear using radiation from a Ho : YAG laser was performed to control a change in the elasticity of the ear cartilage. Variations in the cartilage elasticity were controlled by changes in the amplitude and shape of an acoustic wave during the laser action. It is shown that the optoacoustic signal amplitude exponentially decreases at least by a factor of 2 – 2.5 at the moment of the cartilage reshaping caused by the action of radiation pulses from a Ho : YAG laser.

A controlled reshaping of the cartilage produced by nondestructive laser heating [1 – 3] is a new efficient application of lasers in medicine. This method, which is based on relaxation of strains in the cartilage, allows one to use the bloodless noninvasive procedure instead of the conventional surgery [3, 4]. The relaxation of strains occurs during a fast local heating up to the temperature 65 – 75° C at which water contained in tissues transforms from the bound state to the free state [5].

The aim of this paper is to develop an acoustic method for monitoring mechanical properties of tissues, which are changed during laser processing. Acoustic effects produced by the motion of water in the cartilage upon laser irradiation *in vitro* were observed earlier in [6]. In this paper, we performed for the first time *in vivo* acoustic monitoring of the laser correction of the porcine conch shape.

We used in our experiments a Versa Pulse pulsed Ho : YAG laser with a pulse energy of 23 mJ, a pulse duration of 300 μs, and a repetition rate of 20 Hz. This laser was used for ear reshaping for two reasons. First, its radiation at 2.09 μm provides the optimal relation between the cartilage thickness of the porcine ear (1 – 2 mm) and the depth of radiation penetration inside the cartilage (~ 0.4 mm), resulting in the bulk heating of the tissue. Second, pulsed radiation from this laser generates a detectable optoacoustic response inside the cartilage. As has been shown *in vitro* experiments [6], an acoustic signal caused by the laser-induced optoacoustic response of the cartilage containing water can be detected both in the region of laser irradiation and outside it.

In vivo experiments with ten two-month old young pigs were performed at the Nottingham University in a specially equipped operation room, where young pigs were irradiation by a laser using a proper anesthesiology control and measuring their physiological parameters during the operation.

Fig. 1 shows the scheme of laser irradiation of the porcine conch. To fix the cartilage in the bent state, the conch shape was changed using shaping templates, which served as sound conductors in acoustic monitoring. The end of the porcine conch located between two shaping templates was irradiated. The conch was irradiated through a number of holes made in one of the polypropylene templates. The second template had no holes and was used as an acoustic conductor.

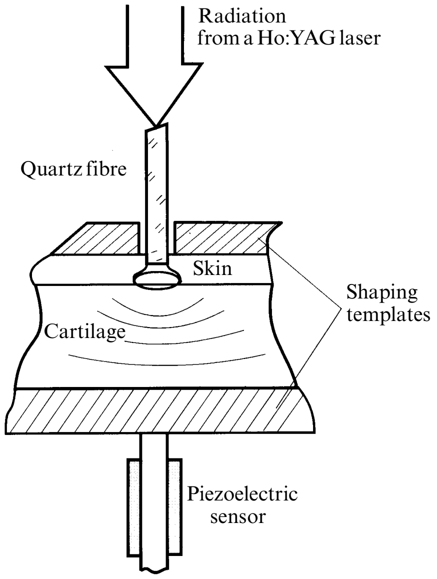

Figure 1. Scheme of laser correction of the shape of the porcine conch.

The porcine ear was irradiated through the holes using a special manipulator that brought a fibre into contact with the cartilage surface. The acoustic contact between a template and a piezoelectric sensor fixed on it was provided with an Ultramix acoustic gel. Acoustic signals were detected with an acoustic probe located on the rear side of the ear at some fixed point.

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Received 12 April 2000
Kvantovaya Elektronika **30** (11) 1031 – 1033 (2000)
Translated by M N Sapozhnikov

The acoustic probe was a quartz sound duct made in the form of a cylinder rod, on which a tubular piezoelectric transducer was placed. Acoustic signals were recorded with an RQ-171 Panasonic tape recorder. The signals were digitised using an Edison Gold 16 sound board and computer processing was performed with the help of the Gold Wave and Origin programs.

Fig. 2 shows acoustic signals detected with a piezoelectric sensor upon laser processing of one point of the conch. One such recording represents a temporal sequence of optoacoustic signals induced by a repetitively pulsed laser. Each optoacoustic response had the shape that was typical for an aperiodic process reflecting the features of propagation of an acoustic wave in a viscoelastic medium. Fig. 3 shows typical acoustic responses at the beginning of laser irradiation, when the cartilage is elastic, and at the end of irradiation, when the cartilage becomes plastic (which corresponds to the decaying part of the curve in Fig. 2).

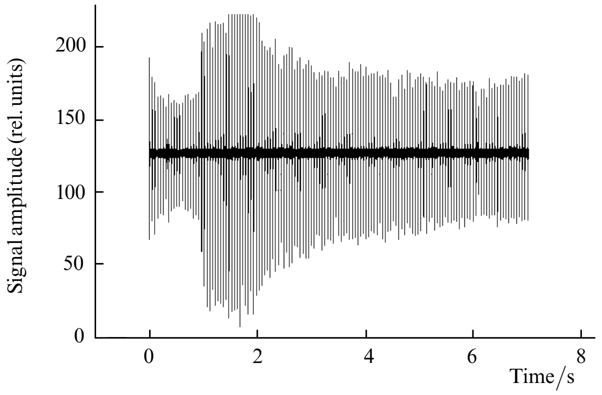

Figure 2. Time dependence of the amplitude of an optoacoustic signal during reshaping of the porcine conch by irradiation of one point of the porcine ear by a laser ($E = 23$ mJ, $\tau = 0.3$ ms, $f = 20$ Hz, the exposure time for one point is $t_{\exp} = 7$ s).

At the moment of the cartilage plasticisation and the subsequent reshaping of the ear cartilage, the optoacoustic-signal amplitude decreases exponentially more than 2 – 2.5 times. The acoustic signals in Figs 2 and 3 reflect variations in mechanical properties of the cartilage caused by laser irradiation. These variations are manifested in the changes in the shape, amplitude, and duration of optoacoustic responses. The pressure amplitude in the compression pulse of such responses of about 80 – 100 kPa and the characteristic *M*-shaped form of the signal are indicative of the thermoelastic mechanism of excitation of an acoustic wave in the cartilage, as in water [7].

The aperiodic nature of the signal detected by a sensor upon irradiation of the conch cartilage and the time dependence of its shape reflected the specific features of excitation and propagation of the acoustic wave in a viscoelastic medium [8]. The signal parameters (the period ~ 1 ms and the oscillation dampimg decrement $\delta \approx 0.4 - 1$) were consistent with the molecular relaxation time ~ 1.2 ms and the damping of oscillations in the cartilage $\delta \approx 0.2 - 1$ that were measured earlier [2]. The duration of the compression phase was determined by the pulse length, while the duration of the rarefaction phase was determined by some characteristic time of the structural relaxation of the cartilage matrix, which depended on its elasticity and the internal friction strength. The internal friction strength determines mechanical losses in the cartilage, which cause the damping of oscillations. According to [2], the damping decrement is related to the relaxation time τ_r by the expression $\tau_r \approx 1/(\delta\omega_0)$, where ω_0 is the frequency of natural oscillations.

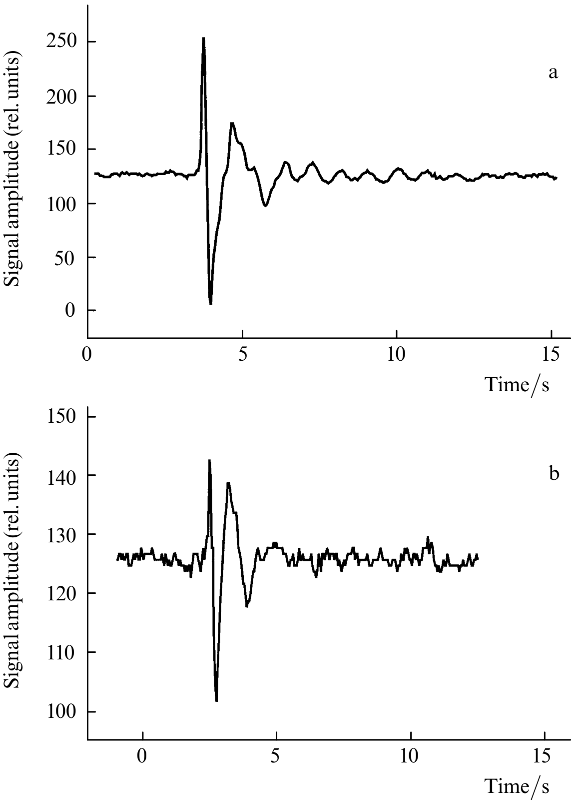

Figure 3. Optoacoustic response of the cartilage at the beginning (a) and at the end (b) of irradiation by a holmium laser ($E = 23$ mJ, $\tau = 0.3$ ms, $f = 20$ Hz, $t_{\exp} = 7$ s).

The behaviour of the response amplitude during irradiation was determined by the position of a fibre through which laser radiation was delivered into the ear tissues with different optical properties. After the irradiation onset, the signal amplitude remained approximately constant for some time and was proportional to the absorption coefficient of the tissue. As the cartilage temperature increased, the signal amplitude and shape changed. The signal amplitude decreased exponentially by a factor of 2 – 2.5 to the end of irradiation and the damping increased.

The dependence of the amplitude of the optoacoustic signal detected on the rear side of the ear on the time of irradiation by a holmium laser during 1 – 2 s is explained by the penetration of a fibre through the skin into the tissues with different absorption coefficients. The exponential decay of the amplitude at the end of irradiation can be caused by a local increase in absorption and scattering of the acoustic wave in the tissue due to its heating. This is confirmed by a decrease in the pressure relaxation time in the acoustic wave in its compression and rarefaction phases compared to the initial relaxation time. The shape of an individual optoacoustic response reflected the properties of the thermoelastic relaxation of strains in the surface layer of thickness $\sim 1/\alpha$ (where $\alpha \leqslant 40$ cm^{-1} is the absorption coefficient of the cartilage [9]).

Thus, we have demonstrated the monitoring of mechanical properties of the cartilage *in vivo* during its irradiation by laser pulses by detecting the amplitude and shape of the acoustic response at some distance from the irradiation point.

Acknowledgements. The authors thank A M Dykhne and V V Zosimov for their permanent interest in this work and useful discussions. This work was supported by INTAS (Grant No 97-1430) and the Russian Foundation for Basic Research (Grants Nos 99-02-16855 and 99-02-16906).

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