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New laser technology and future applications

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Abstract

During the last decades laser technology has continuously developed. New types of lasers as ultra-short pulsed lasers in the femtosecond regime entered medical applications in ophthalmology. Diode lasers became more powerful and smaller with a broader range in wavelengths. In future new sources will also be used in medicine, fibre lasers, LEDs and organic LEDs (OLED). Plastic foils as surface emitters could become important as irradiation source in PDT. But not only progress in light sources opened new fields in medical laser applications, application development with optimised applicators and tool holders widened the spectrum of applications for the same laser, e.g. in dentistry. Microsurgery is still a challenge where nanosurgery in cells already appears. Also new technology in medical diagnostics enter the scene. Optical coherence tomography with high resolution opens the view into the skin or new sophisticated fluorescence microscopy techniques image metabolism of cells. Online diagnosis in combination with laser treatment will open the market and stimulate further development.

Keywords: Laser developments; Light propagation; Monte Carlo simulations; Thermal effects; Laser ablation; Er:YAG laser; Laser diagnostics; Fluorescence lifetime imaging

Introduction

Laser technology has continuously developed during the last 25 years partly driven by the medical demand or adapted from technical applications and transferred to the medical use. There was an up and down in certain therapeutic laser applications making the market really difficult. It happened sometimes because after initially proclaimed successful treatment it turned out that side effects occurred as with the first trials to use the holmium laser for smoothening the surface of cartilage, or the laser treatment was ineffective, not fast enough or the laser treatment became too expensive. Therefore the laser market focussed on ophthalmology, dermatology and microsurgery being more stable in these disciplines. It is also surprising that after strong research efforts in using pulsed Nd:YAG lasers and dye lasers for lithotripsy in the 1980s and beginning 1990s, now the technology appears again in form of pulsed holmium laser and more efficient. On the other hand, photodynamic therapy is still promising already looking back to a long history. Besides the therapeutic use of lasers, the diagnostic possibilities became increasingly important using all specific characteristics of laser light and sometimes even no stimulated emission of radiation. And at present and probably more in the future, the combination of online diagnosis and therapy will be a profitable trend. Following the history of lasers in medicine one has to ask what are the suppositions that make a new laser application and laser development successful? Progress has been achieved with the

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understanding of light diffusion through highly scattering living tissue and simulations of light distribution and the transfer to heat knowing the optical characteristics and the structure of the tissue. This is the basis for the laser tissue interaction, the reaction mechanisms of continuous or short pulsed laser irradiation, and is responsible for the selectivity of laser treatment. And the last but crucial point is the knowledge of the biological reactions and molecular wound healing mechanisms after laser application. With this knowledge the laser parameters can be defined, devices developed and approved in clinical studies.

Basic mechanisms

Three examples shall demonstrate how theoretical considerations and Monte Carlo simulations (MCS) have contributed to determine most effective laser parameters which helped to develop laser technology for specific applications like port wine stain treatment or epilation. In routine dermatological laser applications the coagulation of blood vessels plays an important role. The argon ion laser was the first laser used for port wine stain treatment, successful for deeply coloured lesions. Then the pulsed dye laser seemed to be more effective also for treating children because pulsed laser applications are less painful. But often the results were not satisfying. The lasers were tuned to emit light with 577 nm, corresponding to the last small absorption peak of oxygenated haemoglobin to use the better light penetration into tissue in the red region of the optical spectrum. Kienle [1] could demonstrate (Fig. 1) that at this wavelength and for larger vessels the absorption of the blood was too high for an homogeneous coagulation across the blood vessel. Slightly shifted wavelengths to the red at 585–590 nm are more efficient. With this

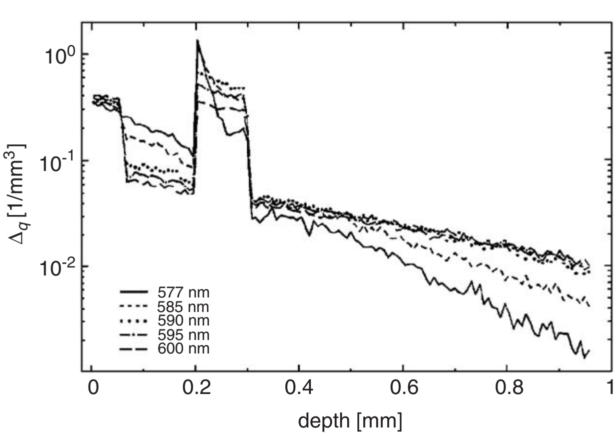

Fig. 1. Simulation of light absorption in blood vessels for port wine stain treatment. Parameters are different wavelengths from 577 to 590 nm.

finding all pulsed dye lasers operate at wavelengths outside the absorption peak around 590 nm for port wine stain treatment. The spot size should be large, preferably more than 10 mm in diameter to enhance the light penetration due to large scattering. For the treatment of teleangiectasia the single vessels are coagulated now efficiently with diode lasers, e.g. at 940 nm, in a longer pulsed mode and with good clinical results. Cooling of the surface is mandatory. This can be achieved by intermittent spray cooling before the laser pulses are released, by using optical clear ice blocks through which the laser pulses penetrate nearly without energy losses or by superficial air cooling keeping the surface wet for a better cooling effect. Comparative studies have been performed in [2].

More recently, laser epilation was a hot topic in dermatology and still is. Cosmetic applications pushed the laser market but also medical indications exist. Ruby lasers (694 nm), Nd:YAG lasers (1064 nm), alexandrite lasers (750 nm) and later diode lasers (810–940 nm) became available. But how to select the most suitable laser type taking into account the pigmentation of the skin? Also this question can be answered performing light perfusion simulations with MCS and calculating the heat flow into the hair, the hair root in depths of 3–4 mm, without damaging the skin surface. In [3] such results are summarised with the conclusion that the alexandrite laser is the most efficient laser because the root damaging effect can be obtained with the smallest radiant exposure of less than 10 J/cm^2 which is 1/3 of the radiant exposure needed with the Nd:YAG laser. Fig. 2 shows a diagram of the damaging integral of such a simulation. For more pigmented skin ($\geqslant$skin type III) the pulsed diode laser has advantages after it became more powerful to treat with larger spot sizes.

Low power lasers for stimulating effects and pain relief are commonly in use with steadily increasing power from milliwatts to now several watts output. Not knowing the exact reaction mechanisms such lasers may have thermal effects on the tissue. To be sure not to damage the skin, temperature simulations are necessary to determine the irradiating spot size which must not fall below threshold. Diode lasers with emission wavelengths of 810 and 940–980 nm (also in combination) are on the market. Fig. 3 gives an example of the temperature profile of such a 4 W laser.

The simulation procedures become more and more complex taking into account the three-dimensional thermal diffusion with energy dissipation by blood flow or the microstructure of the tissue. This is essential, e.g. when calculating the temperature distribution in teeth with the structure of the enamel and the bent tubules in the dentin with light guide effects. More sophisticated simulation procedures are under development profiting from super computer calculation velocities.