Femtosecond Laser – Principles and Application in Ophthalmology

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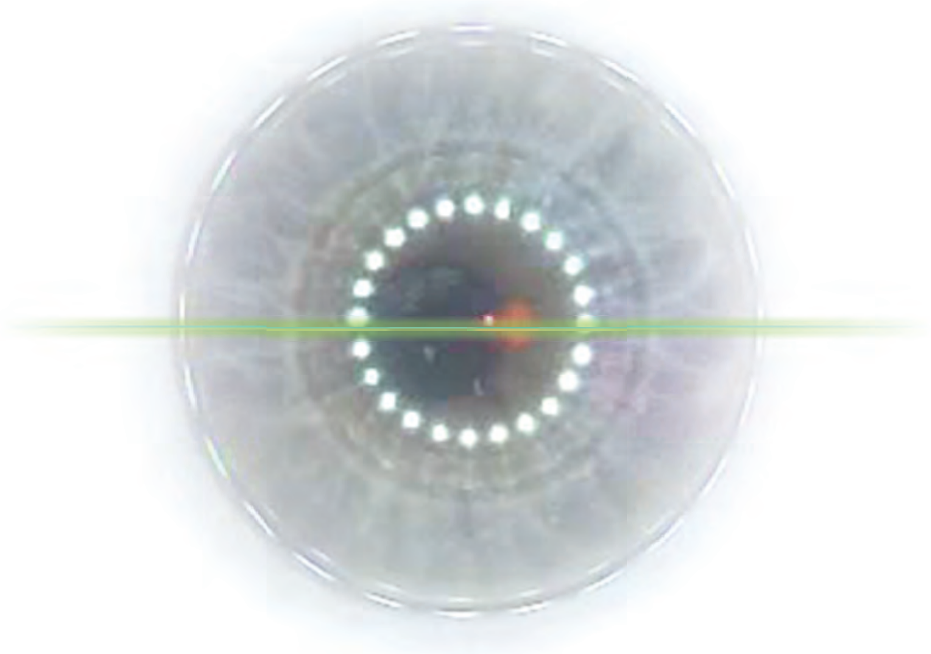

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Preface and acknowledgements

Originally intended only for flap preparation in refractive surgery, use of the femtosecond laser (fs laser) was rapidly extended to the entire spectrum of corneal surgery. The fs laser is now undoubtedly the finest scalpel that allows ophthalmic surgery of the cornea using intrastromal, lamellar or perforating techniques.

This book presents an up-to-date review of the physical and technical bases and the practical clinical applications of this innovative technology in ophthalmology. It is immediately obvious that the fs laser allows new treatments and surgical procedures, some of which would be completely inconceivable using purely mechanical instruments.

The book looks at the beginnings and ongoing further development of fs laser technology, one of the fastest moving fields in ophthalmology. It focuses on both the surgical treatment of clinical diseases, and on the possibility for refractive corrections using fs laser technology.

After a brief historical review, and after an explanation of the physical and technical background, we deal with the practical clinical applications in the form of intrastromal tunnel sections for the implantation of intracorneal ring segments, perforating, anterior and posterior lamellar keratoplasties and AK sections, which are principally used for reduction of astigmatism following corneal transplantation.

The chapter on refractive surgery provides an impressive and succinct illustration of the advantages of fs technology compared with mechanical procedures. The extremely high precision and the possibility of a purely intrastromal operative technique, without having to open the eye at all, represent a genuine advance in refractive surgery.

The book is, of course, only a current snapshot. In the future, there will undoubtedly be other treatment possibilities and indications using this laser technology. We look at some of these at the end of the book.

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Mülheim an der Ruhr, March 2010 *Mark Tomalla*

Foreword

Laser – laser medicine – eye – a brief and historical overview

For a long time the link between medicine and lasers has been regarded by the public as something "sexy"; the reason behind this is the high degree of precision with which it is obviously possible to cut, weld and measure using the laser beam. If we can accurately measure the distance to the moon down to the nearest cm, if time can be measured with the unbelievable accuracy of 10^{-18} seconds, and if atomic nuclear fusion can even be initiated with lasers, then just think what might be possible in the human body. A high level of precision and accuracy are particularly desirable in medicine, or rather in our own bodies if we have to go under the knife.

Unfortunately, the dream of highly accurate laser medicine has not always been realised since many effects of laser beams are too non-specific, usually in the form of local heating in the body. Here, the tissue is carefully warmed, significantly heated up, incised or cut, or even cell-specific destruction takes place. But the more these processes have been studied and analysed in detail and experimentally developed further, the more problems have arisen. Medicine in particular does not involve an immutable "material". The many institutes of laser medicine that opened in prolific numbers throughout the world between 1970 and 1980 have since had to limit their horizons and deal with quite specific as well as more restricted subjects.

However, the public's expectations in laser medicine have been more than met in one area of ophthalmology. Although it is a small area, it is nevertheless a very important one for all of us. This can immediately be seen from the most common surgery that is currently undertaken worldwide every year: not appendectomy or surgery for tonsils and certainly not breast enhancement procedures, but post cataract operations.

It is not surprising that lasers are becoming successful particularly in ophthalmology since ophthalmologists after all are virtually working with light all the time. Their understanding of all things laser, and indeed their enthusiasm for this light source and its possible application in their specialty have undoubtedly, significantly contributed to the triumph of lasers in ophthalmology. There has been the quite incidental and initially almost unnoticed development of a true symbiotic relationship between ophthalmologists and laser physicists without which these sensational new treatment methods would not be conceivable. Fortunately, this symbiosis has played a major role not just for medicine but also, indirectly so to speak, for the laser industry.

The triumphant progress of lasers in ophthalmology was first seen in 1978 when it was discovered that it is possible to re-attach the retina. An Nd:YAG laser was and continues to be used for this; its light is in the near infrared range and is invisible to the eye.

Further progress was made when, at the start of the 1990s, posterior cataract opacifiction (PCO) was found to be a very serious problem in the treatment of cataracts. More and more people developed a secondary cataract since a diffusely scattering membrane formed behind the artificial intraocular lens (IOL). When it was found that this membrane could be destroyed using a short-pulse laser, a specially refined Nd:YAG laser, the way was clear for a broader application in cataract surgery. It is worth discussing this in somewhat greater detail: for the first time, an effect was used that was entirely laser-specific: it is not the heat effect of the laser beam that is important but the high intensity of the light beam. This is because in the presence of laser radiation of particularly high intensity, when a certain threshold is exceeded, a "small explosion" is triggered in the tissue. This tiny "explosion" leads to a small bubble which presses apart the surrounding tissue. When there is one bubble after another, that is, if the laser blasts occur one after another with an appropriately short interval between each blast, this results in the opaque membrane being destroyed. By breaking up the membrane in this manner, it is eventually taken up and removed by the surrounding cells. Light is then able to once again penetrate the remainder of the eyeball unimpeded. The high intensity of the laser beam necessary for bubble formation is achieved by focusing the laser beam in the inside of the eye. It does not interact at the surface of the eye, but only exerts its effect where the beam is focused, similar to the focal point of a burning glass. This extreme focusing is one of the essential properties of laser light.

The next laser success story in ophthalmology began in 1982 when the newly discovered class of ultraviolet light emitting excimer lasers were shown to achieve a special effect on the surface of tissue. The radiation from a special type of excimer laser (argon fluoride laser) is absorbed in very small layers of the surface and converted into heat. However, if the laser energy is high enough, the tissue is vaporised just like the Nd:YAG laser effect described above. Only this time it is not inside the tissue but on the surface, or rather in the surface layer. In this case, only a small part of the laser energy is then converted into heat: most of it is used to break up molecules and thus to vaporise. Above this threshold, the heat is taken up by the vaporised tissue; tissue that has not yet been affected remains cold. This form of tissue removal is therefore also often termed “cold ablation”. It was now therefore possible to “remove” the surface in a highly targeted way, without heating up the tissue. It quickly became clear to ophthalmologists and physicists working together that this tool could be used to process the surface of the cornea in a targeted manner. This was the birth of refractive surgery with excimer lasers. The surface of the eye was specifically altered in such a way that a new curvature of the eye surface allowed new refraction of light.

Since this discovery, more than 20 million people are estimated to have been treated with excimer lasers. They no longer need spectacles or contact lenses, since their refractive error has been able to be specifically corrected using the laser.

This method nevertheless had a minor, more practical drawback: it was not painless for the patient, and analgesics had to be taken for several days. In order to be able to perform the procedure as pain-free as possible, a small layer of the eye surface had to be removed by opening it up. The excimer laser treatment was then performed in the underlying tissue; thereafter, the thin tissue layer was closed again. The LASIK method was born. It is almost painless and has today become the second most common surgery worldwide.

But this LASIK method also had a further obstacle to overcome: only ophthalmologists well versed in the technique were able to make the small tissue incision on the eye with the necessary precision. When performed by less well-trained doctors, the thickness of the corneal flap varied too greatly from patient to patient and the laser treatment could not be undertaken with sufficient reproducibility.

This problem was solved by a new class of lasers, known as the femtosecond laser. Its effect is approximately equivalent to the effect of the Nd:YAG laser described above for the removal of the membrane that occurs from time to time following implantation of an IOL. Only this laser light source has much, much greater accuracy and precision in how it cuts. The energy to produce the gas bubble was reduced a millionfold, yet it is now possible to produce a small, even a very small gas bubble. However, the beam had to be guided with the corresponding accuracy so that a precise tissue layer could be cut. The technical requirements were extreme and it was several years before suitable laser systems were available. The medical industry had to make considerable investments to develop devices with the necessary refinement for medical use. Nowadays, many LASIK treatments use tissue incisions made by an fs laser. Even less experienced doctors are now able to successfully perform the LASIK treatment.

As is so often the case, the improvements in a technology for a specific application lead to new applications in different fields. In this case, the collaboration between ophthalmologists and laser physicists led to a whole host of new ideas for applications for this new laser light source, the fs laser. Fascination with the possibility that there was now a scalpel with phenomenal accuracy and speed for use within the eye led to new ideas coming thick and fast within the period of a few years and these were put into practice.

We are sure that further applications – beyond tissue incisions, keratoplasty, correction of presbyopia and treatments for ametropia – will soon follow. This book gives a first review of this new technology and its applications.

Finally, a few words about myself. I have personally followed laser physics almost since its beginnings and have been involved in some of its developments. The broad spectrum of the special properties of laser radiation is ever-fascinating, especially for a young scientist. The application in medicine was particularly fascinating for me. Directly linking scientific and technical progress with possibilities in medicine is a wonderful experience. The collaboration between doctors and physicists/technicians also allows comprehensive understanding and an insight into other science disciplines, and into the ethics of these as well. The symbiotic relationship with industry should not be forgotten here: it forces us to look more closely at reality and what can actually be achieved.

At this point, and in this context, I would like to extend a very warm and personal word of thanks to Dr Tomalla; he has made a particularly essential contribution to the success of the techniques described in this book. His enthusiasm as well as his creativity in relation to the new technology are exemplary. I would like to also thank him for his efforts in compiling this book in order to make this new technique accessible to a wider audience.

Munich, March 2010 *Dr. Kristian Hohla*

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