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Medizinische Fakultät Mannheim
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Determining the Influence of Environment and Minimizing Residual Roughness in Laser Corneal Refractive Surgery

Autor: Shwetabh Verma
Institut / Klinik: Mannheim Institute for Intelligent Systems in Medicine
Doktorvater: Prof. Dr. J. Hesser

Aims: This dissertation deals with multiple topics, with a global aim of determining the influence of environment and minimizing residual roughness in laser corneal refractive surgery. The multiple topics under consideration are listed below:
TOPIC A: To analyze the effect of seasonal changes in PMMA Performance using the SCHWIND AMARIS laser system
TOPIC B: To analyze impact of various humidity and temperature settings on excimer laser ablation of PET, PMMA and porcine corneal tissue
TOPIC C: To analyze the impact of residual roughness after corneal ablation in perception and vision
TOPIC D: To outline a rigorous simulation model for simulating shot-by-shot ablation process. Furthermore, to simulate the impact of laser beam characteristics like super Gaussian order, truncation radius, spot geometry, spot overlap and lattice geometry on ablation smoothness.
TOPIC E: To test the impact of laser beam truncation, dithering, and jitter on residual roughness after PMMA ablations, using a close-to-Gaussian beam profile.
Methods: TOPIC A: By analyzing PMMA and PET ablation performance by a large series of AMARIS laser systems (Schwind eye-tech solutions, Germany) inside a climate controlled environment, the influence purely coming from the seasonal changes was investigated in a large scale retrospective cross sectional review. Seasonal outcomes were evaluated in terms of PMMA and PET Performance stratified for every month in a year, as well as stratified for each season in a year.
TOPIC B: A Study was conducted using AMARIS system placed inside a climate chamber. Ablations were performed on PET, PMMA and porcine cornea. Impact of wide range of temperature (~18°C to ~30°C) and relative humidity (~25% to ~80%) on laser ablation outcomes was tested using nine climate test settings. Multiple linear regression was performed using least square method with predictive factors: Temperature, Relative Humidity, Time stamp. Influence of climate settings was modelled for Pulse Energy, Pulse Fluence, ablation efficiency on PMMA and porcine cornea tissue.
TOPIC C: The Indiana Retinal Image Simulator (IRIS) was used to simulate the polychromatic retinal image. Using patient-specific Zernike coefficients and pupil diameter, the impact of different levels of chromatic aberrations was calculated. Corneal roughness was modeled via both random and filtered noise, using distinct pre-calculated higher order Zernike coefficient terms. The outcome measures for the simulation were simulated retinal image, Strehl Ratio and Visual Strehl Ratio computed in frequency domain. The impact of varying degree of roughness, spatial frequency of the roughness, and pupil dilation was analyzed on these outcome measures.
TOPIC D: Given the super Gaussian order, the theoretical beam profile was determined following Lambert-Beer model. The intensity beam profile originating from an excimer laser was measured with a beam profiler camera. For both, the measured and theoretical, beam profiles, two spot geometries (round and square spots) were considered, and two types of lattices (reticular and triangular) were simulated with varying spot overlaps and ablated material (cornea or PMMA). The roughness in ablation was determined by the root-mean-square per square root of layer depth.
TOPIC E: A study was conducted using a modified AMARIS system. For the PMMA ablations, two configurations (with a 0.7mm pinhole and 0.75mJ and without pinhole and 0.9mJ (for fluences of 329mJ/cm^2 and 317mJ/cm^2 and corneal spot volumes of 174pl and 188pl)) were considered, along with two types of lattices (with and without ordered dithering to select the optimum pulse positions), and two types of spot placement (with and without jitter). Real ablations on PMMA (ranging from -12D to +6D with and without astigmatism) completed the study setup. The effect of the 2x2x2 different configurations was analyzed based on the roughness in ablation estimated from the root mean square error in ablation.

Results: TOPIC A: The seasons winter and summer showed statistical significant variations with respect to the global values for all the tested parameters except the nominal number of laser pulses for high and low fluence setting. The metric technical performance of the analyzed systems showed a stronger PMMA ablation performance in summer time compared to a weaker performance in the winter time, with the maximum seasonal deviation of 6%. The results were consistently confirmed in seasonal as well as monthly analyses.

TOPIC B: Temperature changes did not affect laser pulse energy, pulse fluence (PET), and ablation efficiency (on PMMA or porcine corneal tissue) significantly. Changes in relative humidity were more critical and significantly affected laser pulse energy, high fluence and low fluence. Opposite trend was observed between the ablation performance on PMMA and porcine cornea.

TOPIC C: In case of a constant roughness term, reducing the pupil size resulted in improved outcome measures and simulated retinal image. The calculated image quality metrics deteriorated dramatically with increasing roughness. Clear distinction was observed in outcome measures for corneal roughness simulated as random noise compared to filtered noise, further influenced by the spatial frequency of filtered noise.

TOPIC D: Truncating the beam profile increased the roughness in ablation, Gaussian profiles theoretically resulted in smoother ablations, round spot geometries produced lower roughness in ablation compared to square geometry, triangular lattices theoretically produced lower roughness in ablation compared to the reticular lattice, theoretically modelled beam profiles showed lower roughness in ablation compared to the measured beam profile, and the simulated roughness in ablation on PMMA tend to be lower than on human cornea. For given input parameters, proper optimum parameters for minimizing the roughness has been found.

TOPIC E: Truncation of the beam was negatively associated to a higher level of residual roughness; ordered dithering to select the optimum pulse positions was positively associated to a lower level of residual roughness; jitter was negatively associated to a higher level of residual roughness. The effect of dithering was the largest, followed by truncation, and jitter had the lowest impact on results.

Conclusions: The large scale retrospective cross sectional study presented in this work, demonstrated a cyclic winter-summer variation in PMMA ablation using the AMARIS lasers. These seasonal variations were further substantiated with the experiments conducted in the climate chamber, over a wide range of temperature and humidity. Temperature changes did not affect laser pulse energy, pulse fluence, and ablation efficiency (on PMMA or porcine corneal tissue) significantly. However, changes in relative humidity were more critical and significantly affected laser pulse energy, high fluence and low fluence. The proposed well-fitting multi-linear model can be utilized for compensation of temperature and humidity changes on ablation efficiency. The relationship between calibration materials like PMMA and corneal tissue shall be analyzed cautiously before designing the calibration routine, in order to obtain optimum outcomes with minimum deviations. Despite its limitations, the simple and robust method proposed here for quantifying the influence of post-ablation roughness on vision and perception, can be utilized in different applications. From the simulations of the shot-by-shot ablation process, a theoretical proper optimum configuration was found for minimizing the roughness in ablation for defined input parameters. The PMMA experiments confirmed the theoretical proper optimum settings in real world conditions. The results and improvements derived out of this work can be directly applied to the laser systems for corneal refractive surgery, to help reduce the complications and occurrence of adverse events during and after refractive surgery, and improve the short term and long term postoperative clinical outcomes.