Error Budget Analysis for Refractive Surgery

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Purpose

- Classification and theoretical analysis of error sources affecting outcomes of refractive surgery.
- Numerical simulation of ablation errors.
- Comparative study and prioritization of error sources.

Classification of error sources

Surgery error sources – anything affecting the final outcome.

Error types (root causes):

1. Technological: machine performance, calibration, algorithms
2. Physiological: immediate tissue response, healing
3. Human errors: deviations from prescribed procedures (doctor or patient)
4. Psychological: differences in patient perception

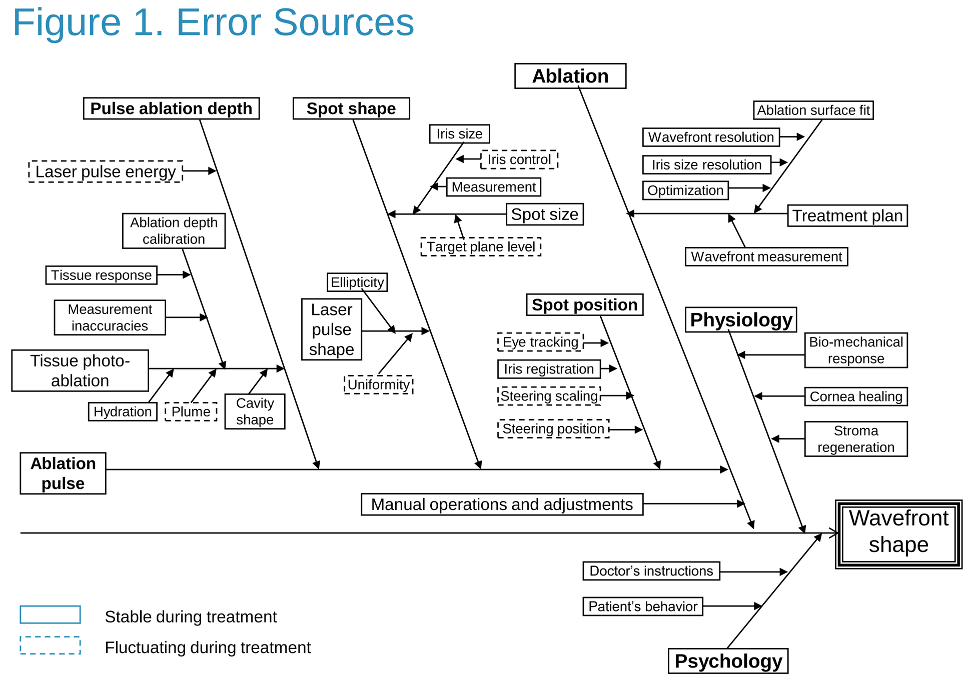
Objective errors:

Treatment plan: inaccuracies of the wavefront measurements, patient examination data, basis data, treatment table optimization.
Positioning: errors in eye registration, eye tracking, laser spot positioning.
Pulse shape: systematic and random errors in the spot size, shape, and uniformity.
Ablation depth: Deviations of a single pulse ablation depth and shape, caused by a variety of factors, both physical and physiological.
Post-operational evolution: bio-mechanical effects and healing process.

Statistical types:

Permanent: modeling of the system calibration, ablation physics, etc.
Alignment: machine-specific deviations in manufacturing, system alignment.
Calibration: stays the same for all treatments until machine is re-calibrated
Treatment: the same for each pulse during a treatment (treatment table errors, machine drift between treatments, etc.)
Fluctuations: random changes from pulse to pulse

Figure 1. Error Sources



Methods

- A GUI-based software was developed for simulation of system errors of surgical laser. Given the laser parameter tolerances it allows a comparative factor analysis of ablation errors and Monte Carlo statistical simulations of wavefront errors, induced by any selected subset of system deviations.
- The error analysis was performed for several treatment types, including myopia, hyperopia, myopic astigmatism, hyperopic astigmatism, and mixed astigmatism.

Figure 2. Software for error budget analysis.

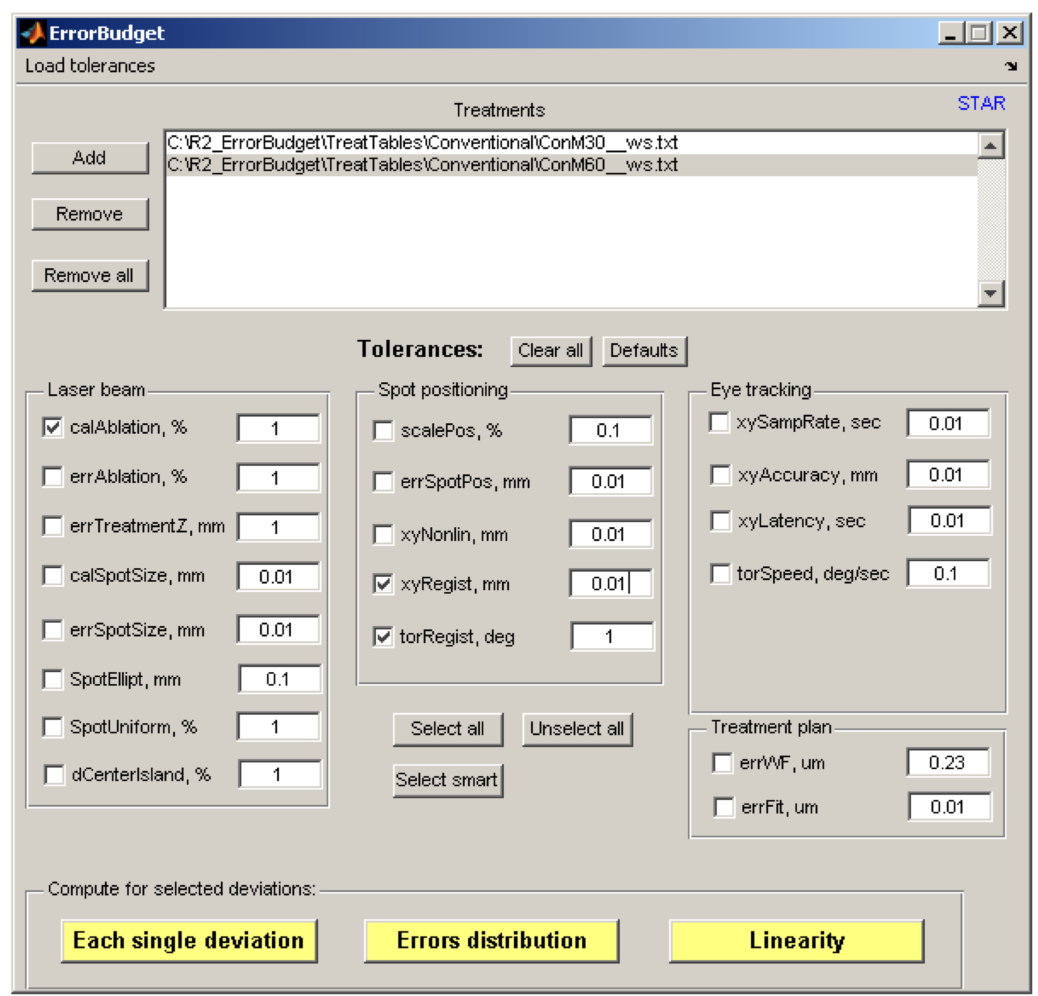
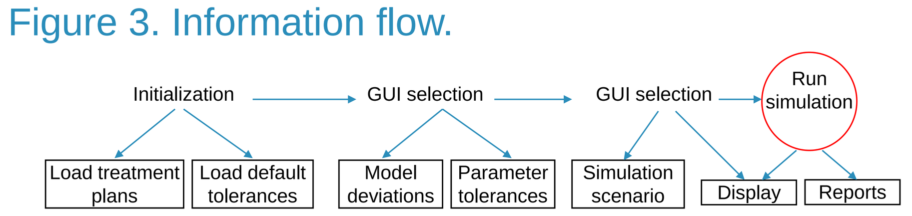


Figure 3. Information flow.



Modes of Analysis:

- Factor analysis. For each error factor, assuming the other factors are perfectly accurate, compute errors for each of the treatments.
- Linearity for each selected parameter. This is done by assigning increasing values to a given system tolerance and compute the errors for each of the value.
- Errors distribution function. Assuming that all error factors may have random values, defined by the Gaussian distribution with the standard deviations defined by their tolerances, compute the distribution of errors.

Results

Monte Carlo simulations:

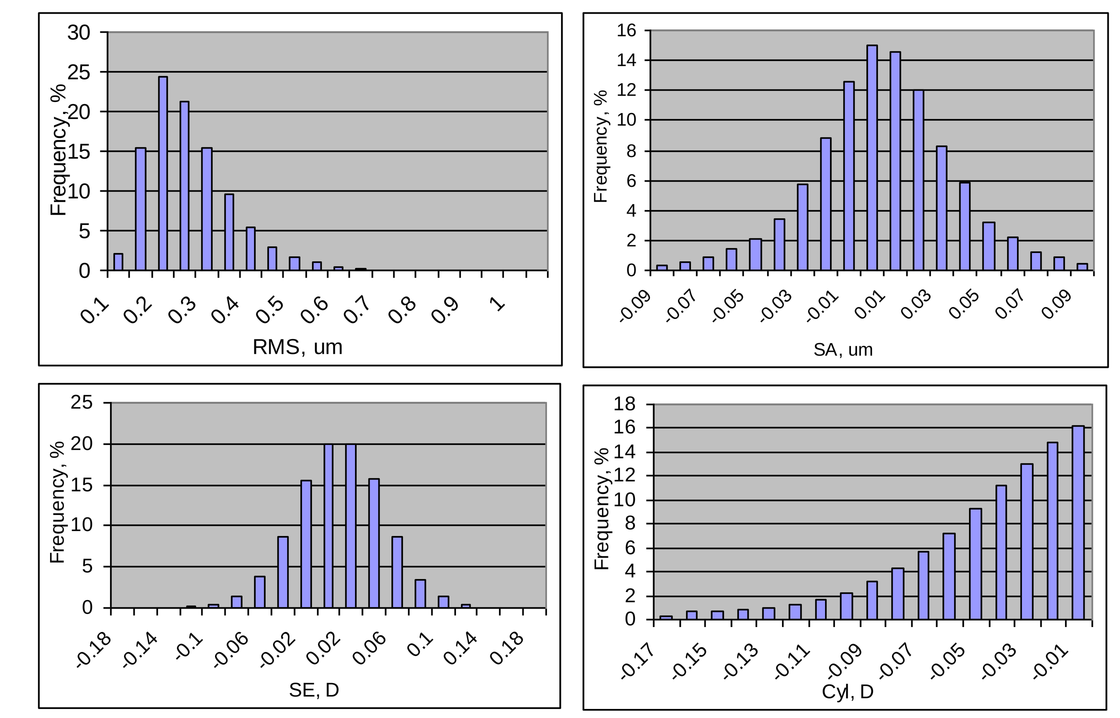
- Treatments with wavefront diameter 6 mm, ablation diameter 8 mm (myopia) or 9 mm (hyperopia)
- Eye tracking errors simulated with eye movement model[3]
- Repetition rate 50 Hz

Figure 4. Comparative factor analysis of errors (95-th percentile).

Wavefront guided treatments | Conventional treatments

Monte Carlo simulations with N=4096 ensemble size.

Figure 5. Simulated distribution of wavefront errors for wavefront guided treatments



Conclusions

- Prioritization of error sources, based on given system tolerances, is needed for further improvement of laser refractive surgery. System development and continuous improvement should concentrate on the fixing the topmost error sources, while the lower error factors will be overshadowed by stronger contributors.
- Systematic errors, which stay the same from pulse to pulse during ablation, are typically most important. Random pulse deviations do not contribute that much to the overall treatment error, because their effect is averaged out by many laser pulses.
- Accuracy of system calibration, spot positioning accuracy, eye registration accuracy, quality of eye tracking, and wavefront measurement error are the most important factors of the total system quality.

References

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3. Ott O., Seidmann S.H.,Leigh R.J. "The stability of human eye orientation during visual fixation", Neuroscience Letters, 1992, 142, 183-186 .