Computer-assisted dosage calculation for strabismus therapy in myopic patients

Martina Koch,[1] Siegfried Priglinger,[2] Robert Hoerantner[1,3] and Thomas Haslwanter[4]

[1]Department of Ophthalmology, University Hospital Graz, Graz, Austria
[2]Good Brothers Hospital, Brüder, Linz, Austria
[3]Good Brothers Hospital, Schwestern, Ried, Austria
[4]Upper Austrian University of Applied Sciences, Linz, Austria

ABSTRACT.

Purpose: **The published dosage recommendations for the surgical correction of horizontal strabismus in non-myopic patients show large, unexplained differences. For patients with high myopia, the situation becomes even more complex because the increase in the size of the bulb also affects the geometry of the oculomotor muscles. In this study, we wanted to investigate whether computer simulations of the oculomotor plant can be used to find accurate surgical parameters.**

Methods: **In a retrospective study, we investigated pre- and postoperative strabismus patterns in 13 patients affected by convergent (seven patients) or divergent (six patients) strabismus and high myopia. Postoperative checks were made 1 day, 1 week, 3 months and 1–6 years after the operation. For each patient, we simulated the presurgical strabismus pattern with SEE++ (see 'Further Information' for manufacturer details), a biomechanical simulation program of the oculomotor plant. The individual results of the simulations were then compared to the measured postoperative strabismus patterns.**

Results: **We found a trend of under-correction in the postoperative situation, resulting in four patients having a large remaining strabismus angle of more than 5 degrees. The computer simulations were able to reproduce this under-correction, and suggested an increase in dosage.**

Conclusion: **We conclude that realistic biomechanical simulations of the oculomotor plant can predict the postoperative result for myopic patients accurately. The results of the computer simulation correlate well with the postoperative outcome of the patient.**

Key words: myopia – oculomotor mechanics – strabismus – surgery – systems modelling

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Introduction

In ophthalmology, one regularly encounters patients with 'strabismus convergens' or 'strabismus divergens'. Patients affected by a constant horizontal strabismus angle are usually treated with ocular muscle recession and resection or plication (Dyer 1971; Rosenbaum & Santiago 1999; Lang 1995; Kaufmann 1994). Different textbooks and publications suggest different dosages for horizontal strabismus surgery. For example, the four established textbooks by Dyer (1971), Rosenbaum & Santiago (1999), Lang (1995) and Kaufmann (1994) suggest dosages that vary by more than 200%. While the effect of the bulb size on the efficacy of the muscle displacement is known (Graf et al. 1994; Simonsz 1990), this effect is only discussed by a few publications (Brooks et al. 1989; Gillies & Hughes 1984; Gillies & McIndoe 1981, 1982). Because of the wide range of dosage suggestion in subjects with normal globe diameter and the rare occurrence of patients with larger globe diameter, we investigated 13 patients with high axial myopia before and after surgery. For the computer simulation of the strabismus and of the effects of surgery we used SEE++ (see 'Further Information' for manufacturer details), a powerful, easy-to-use simulation program for oculomotor mechanics that has been developed by Buchberger and coworkers (Buchberger 2004; Haslwanter et al. 2005). The computer model was used to examine the effect of high axial diameter on the surgical dosage for strabismus correction. The main aim of this study was to compare the observed dose–effect relationship in patients with axial high myopia and strabismus to the individualized dosage suggestions of a biomechanical simulation of the oculomotor plant.

Materials and Methods

Subjects

Our study includes 13 patients, seven with convergent and six with divergent deviation. According to the Declaration of Helsinki, all patients or their legal representatives were informed about possible side-effects, and written consent for the operation was obtained. To obtain a reasonably large number of subjects, we searched our patient database of the last 20 years for all patients who presented with high myopia (more than −8 dioptres) and large axial globe diameter, who received surgical treatment for convergent or divergent strabismus (Jacobsen et al. 2007). We excluded patients with vertical deviations in primary position, which can occur with high axial myopia (Krzizok & Schroeder 1999, 2003), and patients with previous surgical treatments. In all cases the strabismus pattern was concomitant, and the shortest follow-up time was 1 year. Ten patients showed slight additional motility disorders in extreme globe position (30 degrees ad- or abduction, 30 degrees elevation or depression). The average visual acuity was 0.31 ± 0.27 [mean ± 1 standard deviation (SD)] on the higher myopic eye and 0.74 ± 0.22 on the other eye. Patients with low visual acuity were not excluded (three patients had a visual acuity of less than 0.05). We also optimized amblyopic therapy before surgery (Koskela et al. 1991; Lundh 1986). To determine the effect of this surgical intervention, subjects were tested before the operation, 1 day, 1 week, 3 months and 1–6 years after the operation (Shauly et al. 1997). Patients' age was 28.4 ± 21.1 years (range 3.7–59.9 years) (Gronlund et al. 2006). Myopia on the higher myopic eye was −12.8 ± 2.9 dioptres (range −9.4 to −19 dioptres), and the average myopia of both eyes was −8.9 ± 5.8 dioptres (Nielsen et al. 2007).Bulb diameter was determined with ultrasound. The operated bulbs had a diameter of 31.4 ± 5.9 mm (mean ± SD). In four patients with large bulb diameter, the shape of the bulb was quite elliptical; as a result, the ultrasound measurements of the bulb diameter were quite variable. Therefore, these measurements were not included in our calculations.

Strabismus measurement

The strabismus angle during fixation with the left eye and during fixation with the right eye was determined using the corneal light reflex, the cover test and prism cover test, with optimal refractive correction (Zehetmayer et al. 1994). The strabismus angle was measured for far fixation (600 cm) and near fixation (40 cm). Refractive correction was determined under cycloplegia by skiaskopia (retinoskopia).

Treatment

Common recession and resection or plication was performed for convergent or divergent deviation (Gezer et al. 2004; Bagheri et al. 2001; Rajavi et al. 2001; Stark et al. 1999; Lennerstrand 1986; Klyve & Nicolaissen 1992). The operation was employed on the eye that was used less frequently for fixation. Based on the preoperative deviation, the amount of recession and resection or plication was calculated according to the values given by Kaufmann (1994) and Lang (1995), as described later in this article. The calculated dosage was transferred to the bulb and muscle with a caliper and methylene blue marking. The effect of recession and resection or plication on the strabismus angle was rated as equal. The necessary amount of muscle surgery was calculated based on the preoperative deviation. For treatment, this amount was split approximately 1 : 2 (recession one part, resection or plication two parts). This division was necessary to keep the amount of recession small and to preserve a sufficiently long arc of contact of the muscle. The expected effect of muscle displacement by 1 mm was calculated with 1.74 degrees ± 0.35 degrees. The dosages used for exotropia (1.79 degrees ± 0.39 degrees per 1 mm muscle change) and esotropia (1.7 degrees ± 0.34 degrees per 1 mm muscle change) were statistically indistinguishable.

Computer model and simulation

For each patient we compared the preoperative angle of deviation, the surgical parameters and the postoperative deviation with the corresponding data from a computer simulation. For these simulations we used the oculomotor model SEE++ and individualized parameters for each patient (Buchberger 2004; Haslwanter et al. 2005). To simulate the preoperative strabismus pattern, we first focused on the strabismus angle in the primary position. Figure 1 shows the simulation of a patient whose bulb diameter was 30 mm in both eyes, and who showed 17.5 degrees convergence in the primary position.

To model this deviation, we changed the muscle lengths to obtain a concomitant eye movement pattern: the medial rectus was shortened by 6.4 mm, and the lateral rectus lengthened by 7.5 mm. Figure 1B shows the resulting presurgical strabismus pattern.

Other modifications that would also generate this deviation in the primary position but would produce an incomitant pattern were not considered here. The patient shown in Fig. 1 was treated with a 4 mm recession for the medial rectus muscle and a 6.5 mm resection of the lateral rectus muscle. Figure 1C shows the simulated postoperative strabismus pattern, with a strabismus of 1 degree in primary position (as calculated by SEE++). The patient had 2 degrees esotropia when examined with the prism cover test in primary position postoperatively.

Statistical parameters

Because of the small number of patients ($n = 13$), a non-parametric test was used. To test if parameter changes within subjects were significant, we used the two-sided Wilcoxon matched-pairs signed-ranks test without (for $t_0 > 2$) and with (for $t_0 \le 2$) continuity correction. We tested for a significance level of $P < 0.05$. To compare esotropia and exotropia (different subject groups), we used the Wilcoxon rank sum test (Mann–Whitney U-test) for unpaired data.

Results

Figure 2 shows the surgical effect on the deviation in primary position. In the white region to the left, the preoperative strabismus deviations are given; the white areas to the right contain the predictions of the postsurgical strabismus that we obtained from the

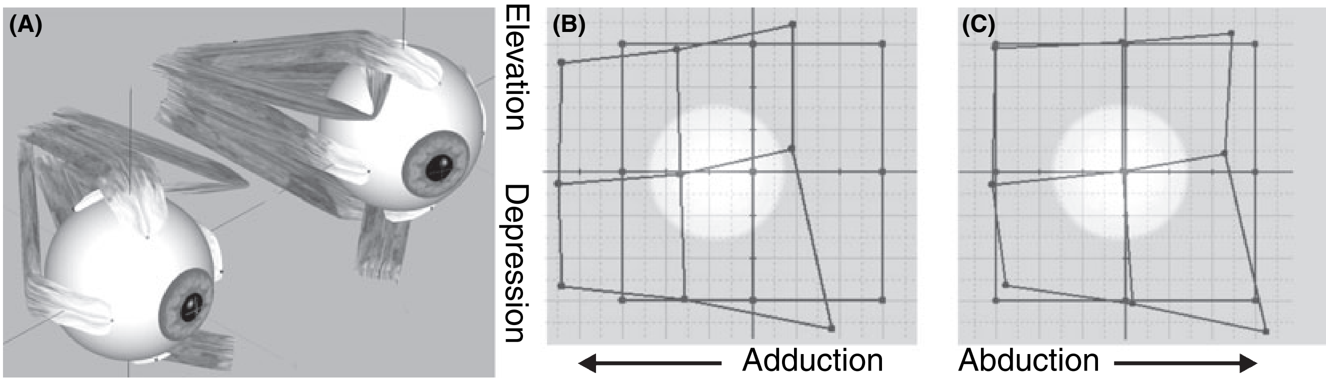

Fig. 1. Simulation of strabismus patterns. (A) Three-dimensional animation of a patient with esotropia (screenshot from SEE++). (B) Simulation of the preoperative situation, as described in the text. (C) Simulation of postoperative strabismus pattern. 'Adduction' and 'abduction' refer to the viewing direction of the non-fixing eye.

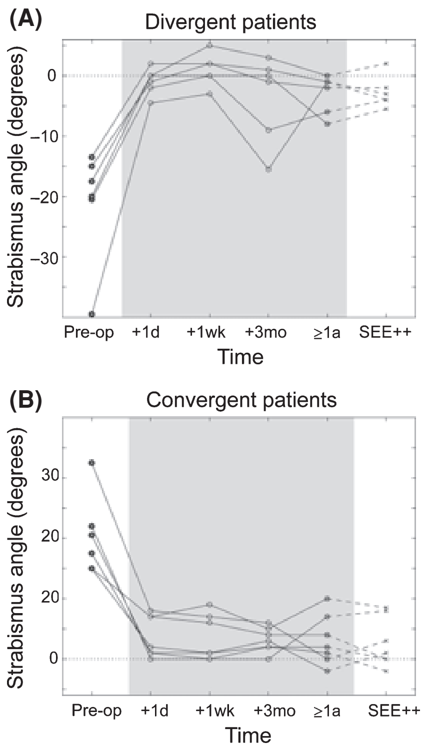

Fig. 2. Strabismus angles of exotropia (A) and esotropia (B) patients as a function of time. The white area on left shows the preoperative situation; the grey box shows the postoperative course of deviation; the white area on the right shows the simulation results with SEE++. (Three patients with esotropia had the same preoperative deviation, thus only five points are visible on the left side.)

computer simulations with SEE++. Divergent patients show good results 1 day and 1 week after surgery, and a (non-significant) trend to under-correction later on. Convergent cases always had under-correction after surgery.

Dosage and strabismus angle

To determine the effectiveness of surgical interventions, we analysed the long-term results (1 year or more postoperatively), which are presented on the right-hand side of the grey regions in Fig. 2. Per 1 mm muscle change (recession or resection/plication), the measured change in strabismus angle was 1.42 degrees ± 0.46 degrees (1.36 degrees ± 0.51 degrees in esotropia, 1.5 degrees ± 0.42 degrees in exotropia). The difference in the values for esotropia and exotropia was not significant. The actual efficacy of a muscle change by 1 mm was significantly different to the expected effect of 1.74 degrees ($P = 0.019$, Wilcoxon matched-pairs signed-ranks test). In comparison, the simulations with SEE++ predicted an effect of 1.48 degrees ± 0.32 degrees, which is statistically indistinguishable from the measured postoperative values.

The difference between the postoperative results of the patient situation 1 year or more after surgery and the simulation of SEE+ + was 2.4 degrees ± 1.14 degrees. The Wilcoxon matched-pairs signed-ranks test showed no significant difference between deviation change in the patient situation and in the simulation with SEE++. The angle of deviation before and at different times after the operation was significantly different in both patient groups. The Wilcoxon matched-pairs signed-ranks test showed *P*-values of less than 0.05 (Table 1).

Postoperative deviation of more than 5 degrees

In four of the 13 cases, the remaining strabismus deviation was more than 5 degrees (Table 2). This under-correction was the result of the chosen surgical parameters, and was for each patient reproduced by the computer simulations in SEE++. In other words, the error in postoperative strabismus deviation could have been avoided by using a realistic biomechanical simulation, like SEE++. For the four patients who showed a remaining strabismus angle of more than 5 degrees 1 year after surgery (two divergent and two convergent), the explicit values are given in Table 2.

Discussion

The position of the human eye is affected by the biomechanics of the oculomotor system, as well as by the nervous response to sensory inputs from this system. In surgical manipulations of the eye, we try to optimize the biomechanics to reduce strabismus deviation as much as possible.

Because the biomechanics of the eye are surprisingly complex, simple rules of thumb are not sufficient to reflect the individual structures for each patient. As a result, surgical recommendations vary by more than a factor of two, even for non-myopic patients. In patients with high myopia, the biomechanics become even more complex because the increase in the size of the bulb also affects the geometry of the oculomotor muscles.

In our study, we found that realistic simulations of the oculomotor system such as SEE++ help to control this complexity, and allow practitioners to predict the individual responses to surgical changes like resection, plication

Table 1. Strabismus angle (in degrees) before and after operation (mean ± 1 standard deviation). Convergent values are positive, divergent values negative. *P*-values of comparison before and after surgery (Wilcoxon matched-pairs signed-ranks test).

		Postoperation				
	Preoperation	1 day	1 week	3 months	> 1 year	Simulation
Convergent ($n = 7$)	19.6 ± 6.3	3.7 ± 3.5	3.4 ± 3.8	3.1 ± 2.0	3.1 ± 4.2	2.6 ± 4.1
P (versus preoperation)	–	0.0178	0.0180	0.0180	0.0180	0.0180
Divergent ($n = 6$)	−21 ± 9.5	−0.9 ± 2.2	1.0 ± 2.7	−3.6 ± 7.1	−3.0 ± 3.2	−2.4 ± 3.4
P (versus preoperation)	–	0.0277	0.0277	0.0277	0.0277	0.0277

Table 2. Cases with remaining strabismus angle of 5 degrees or more after treatment, in comparison to the simulation result of SEE++. Using the actual surgical parameters, SEE++ calculated almost the same remaining strabismus angle as found in the patients (low dosage).

	Patient data		Deviations		SEE++	
	Globe diameter on side with surgery (ultrasonic)	Surgical parameters (value and muscle)	Preoperation	Postoperation	Prediction with used surgical parameters (row 3)	Surgical parameters suggested for optimal results
Patient 8	26.3 mm	Recession: 4.0 mm rect. lat Resection: 7.0 mm rect. med.	−20.5 degrees	−6 degrees	−4 degrees	Recession: 5.0 mm rect. lat Resection: 8.0 mm rect. med.
Patient 9	27.4 mm	Recession: 4.0 mm rect. lat. Resection: 7.0 mm rect. med.	−20 degrees	−8 degrees	−5.5 degrees	Recession: 5.0 mm rect. lat. Resection: 7.8 mm rect. med.
Patient 12	Value inaccurate	Recession: 2.5 mm rect. med. Resection: 5.0 mm rect. lat.	+15 degrees	+10 degrees	+8 degrees	Recession: 4.0 mm rect. med. Resection: 5.5 mm rect. lat
Patient 13	35.0 mm	Recession: 4.0 mm rect. med. Resection: 8.0 mm rect. lat.	+22 degrees	+7 degrees	+8.5 degrees	Recession: 5.0 mm rect. med. Resection: 10.0 mm rect. lat.

Rect. lat., lateral rectus muscle; rect. med., medial rectus muscle.

or recession. This can lead to a significant improvement in the determination of the surgical parameters for minimizing the strabismus angle.

The use of a realistic biomechanical simulation also provides a way to separate the biomechanical and the sensory contributions to the observed strabismic behaviour. The results of our simulations indicate that in our patients the interrelations between biomechanical and sensory effects were probably small: in our esotropic cases the operative effect is constant up to 1 year after treatment; in the six exotropic cases the effect decreases slightly but not significantly 1 year after treatment (exoshift) (Stager et al. 1994; Happe & Suleiman 1999).

The computer model SEE++ provides the possibility of modifying all static and dynamic oculomotor parameters, allowing the simulation of almost every type of strabismus in an exact and biomechanically appropriate way. For our patient group, the simulation results corresponded well with the measured strabismus angles, and the consistent under-correction could have been avoided by using the dosages suggested by SEE++. Our retrospective study, with a relatively small sample size, shows the possible advantages of using a simulation system such as SEE++. An improved validation of SEE++ could be obtained by a randomized, prospective study with a larger sample size.

Further Information

The SEE++ software system can be purchased from the Upper Austrian Research (UAR) Department for Medical Informatics. The UAR GmbH is a non-profit organization funded by the local Upper Austrian government, and any earnings are reinvested into further development of the SEE++ software system.

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Correspondence:
Robert Hoerantner
Krankenhaus der Barmherzigen Schwestern, Ried
Schlossberg 1
4910 Ried
Austria
Tel: + 43 7752 602
Fax: + 43 7752 602 6560
Email: robert.hoerantner@bhs.at