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Sixty strabismus cases operated with the Computerized Strabismus Model 1.0: When does it benefit, when not ?

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Abstract While, in routine strabismus surgery, empirical guidelines and experience are the best in judging which eye muscles to operate, a complex case may need a unique surgical approach, the consequences of which cannot always be envisioned in detail. We sought to improve the results of surgery in these cases by preoperative simulation of each case with the Computerized Strabismus Model 1.0 (CSM). The basis of this model was laid by David A. Robinson. It has been improved by us over the past years to the point that it can be used clinically. Improvements concerned, for example, the mechanics of the eye muscles and the anatomy of insertions and origins. The ease of operation has been improved and the algorithms have been made so much faster that a full calculation for 9 positions of gaze now takes 10 seconds on a hand-held Hewlett Packard 200LX Palmtop. From 1994 onwards, all cases to be operated in our department which were more complex than straightforward horizontal rectus muscle surgery were simulated in the model preoperatively. The predictions of the model compared well with the actual result of surgery in most cases. The model was particularly good in handling complex and unique disorders of motility. However, the model could not reliably predict the effect of strabismus surgery in cases with mechanical restrictions of motility.

Keywords Strabismus surgery; eye movement disorders; esotropia; exotropia

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This paper was presented in part at the XXIII Meeting of the European Strabismological Association, Nancy, June 6-8, 1996[1].

Introduction The clinical use of the Computerized Strabismus Model 1.0 (CSM) is reported below. This computer program was originally conceived by David A. Robinson[2] and has now been developed to the point that it can serve as an advisor in strabismus surgery. There are two offspring of Robinson's strabismus model that are currently used clinically. Joel Miller's model[3] is commercially available. Ours is distributed as shareware and can be downloaded from the AAPOS Homepage (http://med-aapos.bu.edu – this is a compressed ZIP file to be unzipped with Pkunzip 2.04) thanks to Rick Blocker MD from Buffalo University, the editor of the AAPOS Homepage. The model was recently described in detail.[4] A concise description follows.

The strabismus model consists of two computer programs packed with formulas. The first program derives the levels of innervation of the six eye muscles from a given eye position (angle of strabismus), whereas the second program derives the eye position from the six levels of innervation. Both programs use the same set of parameters describing the anatomy of an average eye (eye size, insertions and origins) and the mechanical properties of the eye muscles. However, in the second program, which derives eye position from innervation, these parameters can be changed so that, for instance, surgery can be modeled.

In the first program, the user starts by entering the angles of strabismus in nine positions of gaze (five, three or one position of gaze is also possible), i.e. in 25°/25° left upgaze, 25° upgaze, etc. The angles of strabismus are converted by the program to absolute eye positions and the program calculates the force and length of the six eye muscles needed to keep the squinting eye in these nine directions of gaze. As the relation between force, length and innervation of the eye muscles is known (Fig. 1), the level of innervation of the six eye muscles can be derived from the first two variables. These levels of innervation, the output of the first program, are stored in a file on harddisk, together with other information concerning this case.

In the first program, the axial length of the eyes of the patient can be adjusted to fit the age and refraction of the patient. From the axial length, a scaling factor is derived that is used throughout the program to multiply all values that are subject to change with the size of the eye. Either eye can be designated as the strabismic eye and angles of strabismus can be entered for fixation at near or fixation at distance. The parameters in the formulas describing the mechanical characteristics of the eye muscles are valid for average eye muscles, as measured *in vivo* in awake patients that were operated for strabismus under local, eye-drop anesthesia.[5] For experienced users there is a possibility, however, to alter the default mechanical properties of the model eye muscles in the first program.

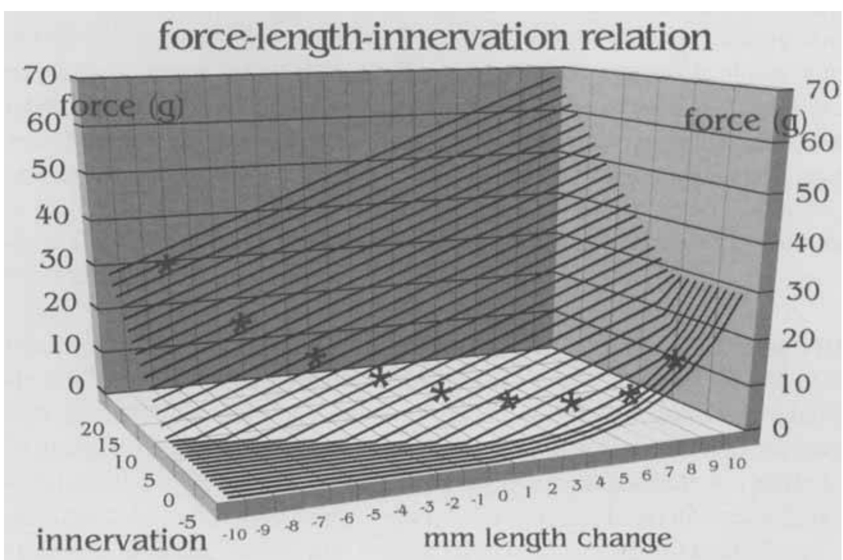


Fig. 1. The force-length-innervation relation used in CSM; here, the relation for the medial and lateral rectus muscles is depicted. The change in length of the muscle (mm) is shown on the abscissa, the level of innervation of the muscle is shown on the ordinate and the vertical axis represents the force of the muscle (g). At low levels of innervation (muscle not actively contracting), the force is zero at gaze-ahead length, to rise exponentially when the muscle is stretched. At high levels of innervation (muscle strongly contracting), the force-length relation is linear.

During eye movement and eye acceleration, as well as during measurements of eye muscles that are separated from the globe, many combinations of force, length and innervation are possible. When the eye is not moving, however, e.g. during the measurement of the angles of strabismus, only one level of force, length and innervation applies for each position of gaze. This curve in the diagram is represented by a series of asterisks, for 40°, 30°, 20°, 10°, primary position, −10°, −20°, −30° and −40°, respectively. Note that the innervation parameter does not represent the true firing rate of the neurons, but is deduced from other variables and can therefore acquire a negative value.

The second program prompts the user for the patient's name and collects his file. Then the user can enter all types of strabismus surgery: recession, resection, transposition or Faden operation. Forced duction can be modeled. A palsy is modeled by decreasing the innervation of a muscle. Overaction is modeled by increasing the innervation of a muscle (a simplification, as the eye motility described by 'overaction' actually has a multivariate cause).[6] Finally, fibrosis of a muscle can be modeled by changing the force-length relation of the non-contracting eye muscle: the muscle can be made shorter, stiffer or both. To model a palsy of an eye muscle, the user starts with a normal eye, by entering 0° angles of strabismus in the first program, and then models a palsy by decreasing the innervation of a muscle in the second program.

The second program first calculates the positions of the origins and the insertions that may have been changed by surgery. It then calculates the position of the strabismic eye for nine directions of gaze. From the absolute eye positions the angles of strabismus are derived. These are presented graphically, in a way similar to a Hess chart.

When the other, fixating eye is also being operated, the levels of innervation of that eye are first calculated instead, assuming that eye fixated the 25°/25° positions during the measurements of the angle of strabismus. Then the user can enter all types of strabismus surgery, palsy or fibrosis for that eye. The second program then calculates the position of the fixation eye for nine directions of gaze. Then the angles of strabismus are derived and presented graphically.

The ease of operation and the algorithms have been optimized so that the model now runs on a hand-held Hewlett Packard 200LX Palmtop in 10 seconds for a full calculation in nine positions of gaze. For comparison, the model initially took 5 minutes on an IBM PC. The program runs well on any IBM- compatible, but the fact that the program runs well on a hand-held PC is relevant: In our experience it is not really possible to interrupt the preoperative examination of a patient to find a desktop PC to do some calculating, while the use of a hand-held PC is well accepted by patients, especially when their case is complex.

Materials and methods A comprehensive description of the model, with discussion of the modifications, has been published recently.[4] The most important modifications concerned the anatomy and the mechanical properties of the eye muscles. For instance, the data on the location of the origins and insertions of the eye muscles was improved with data from Fink,[7] Lang et al.[8] and many others. The size of the eye, as related to age and refraction, was adjusted with data from Larsen[9] and others. The formula that describes the relation between force, length and innervation of an eye muscle was improved with a separate study[5] in which, in 32 patients, the force and length of rectus and oblique eye muscles were measured during strabismus surgery under local, eye-drop anesthesia (Fig. 1). In these measurements, the muscle was cut off from the globe and the relation between force and length of the muscle was determined at three different levels of innervation: the patient first looked straight ahead for one minute with the other eye, then one minute into the ON direction and then one minute into the OFF direction of the muscle that was measured.

Finally, the direction of pull of the eye muscles during eye movements out

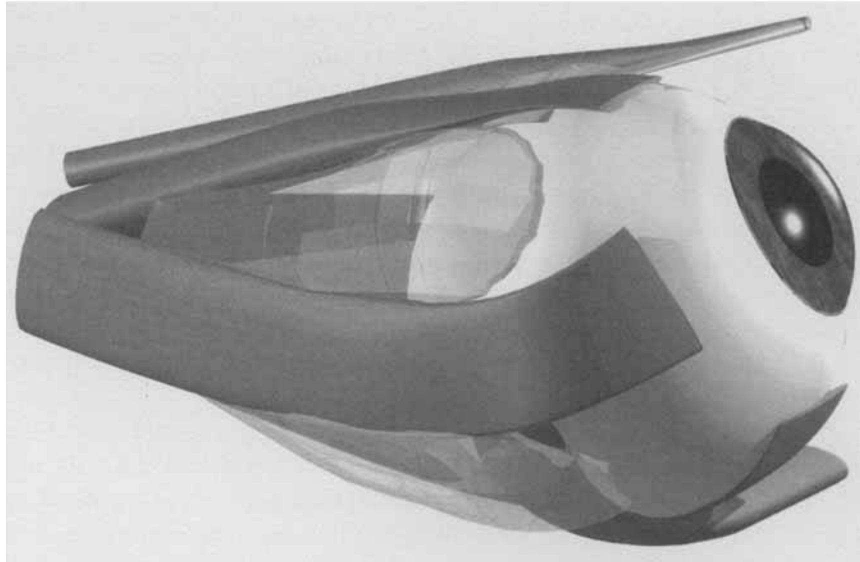


Fig. 2. Illustration of what happens with the direction of pull of a lateral or medial rectus muscle when the eye looks upward. If the muscle were to follow the shortest path under all circumstances, the muscle belly would displace cranially. However, this does not happen. The eye muscles are suspended in connective tissue sheets like the intermuscular membrane that prevent sideways displacement of the muscle belly during eye movements out of the plane of the muscle. The tension in the intermuscular membrane preventing sideslip results from the retrobulbar pressure, which again results from the four rectus muscles pulling the eye into the orbit and is partly contained within the muscle cone.

of their plane of action is a crucial and hotly discussed topic in strabismus modelling. It is easy to calculate the direction of pull when the eye looks straight ahead, but what happens with a medial rectus muscle, for instance, when the eye looks upward? If the muscle were to follow the shortest path under all circumstances, the muscle belly would displace cranially. As we know by now, this does not happen.[10-12] The eye muscles are suspended in connective tissue sheets like the intermuscular membrane that prevent sideways displacement of the muscle belly during eye movements out of the plane of the muscle (Fig. 2). We hypothesized previously[10] that the tension in the intermuscular membrane preventing sideslip results from the retrobulbar pressure (about 4 mm Hg),[13] which again results from the four rectus muscles pulling the eye into the orbit and is partly contained within the muscle cone.

Demer and Miller[12] call the mechanism of connective tissue sheets preventing sideslip the muscle pulley and emphasized, in a recent MRI study, their connection to the orbital wall.[14] If sideslip is prevented by connective tissue sheets connected to the orbital wall, one would expect the force needed to keep the muscle belly in place to dissipate mainly into the orbital wall. For instance, in the above example, the force directed caudally that keeps the belly of the medial rectus muscle in place when the eye looks upward would dissipate via the muscle pulleys into the orbital wall.

Alternatively, if sideslip is prevented by the tension in the intermuscular membrane, caused by the retrobulbar pressure caused by the four rectus muscles pulling the eye into the orbit, one would expect the force needed to keep the muscle bellies in place to dissipate into the intermuscular membrane and thereby into the other rectus muscles and anteriorly into the eye. Now, if the force were to dissipate fully into the orbital wall, the direction of pull would fully rotate with the eye during eye movements out of the plane of the muscle (Fig. 3, arrow 2). If the force dissipated fully into the eye, the effective direction of pull of an eye muscle would remain constant in the orbital frame (Fig. 3, arrow 3). Clement[15] was the first to analyze the influence of the direction of pull with the help of the computerized model. He compared six versions of his model with different directions of pull.

We compared two versions of the model (direction of pull rotating with

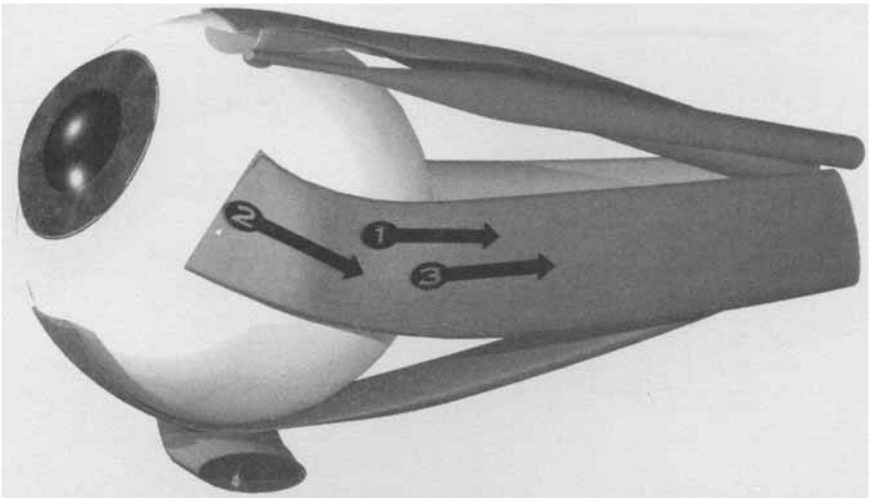


Fig. 3. Diagrammatic representation of the direction of pull of the muscle during eye movements out of the plane of the muscle in relation to the direction of dissipation of the force needed to keep the muscle belly in place. If sideslip is prevented by connective tissue sheets connected to the orbital wall, one would expect the force needed to keep the muscle belly in place to dissipate mainly into the orbital wall. For instance, in this example, the force directed caudally that keeps the belly of the medial rectus muscle in place when the eye looks upward would dissipate via the muscle pulleys into the orbital wall. If the force dissipates into the orbital wall, the direction of pull of the muscle rotates with the eye during eye movements out of the plane of the muscle (arrow 2). Alternatively, if sideslip is prevented by the tension in the intermuscular membrane, caused by the retrobulbar pressure caused by the four rectus muscles pulling the eye into the orbit, one would expect the force needed to keep the muscle bellies in place to dissipate into the intermuscular membrane and thereby into the other rectus muscles and anteriorly into the eye. If the force dissipates into the eye and other eye muscles, the effective direction of pull of an eye muscle remains constant in the orbital frame (arrow 3). We compared the two versions of the model with clinical measurements in a large series of palsy and strabismus operations and found the differences between the two to be small. However, pull at the point of tangency, as in Robinson's original model (arrow 1), yielded more variable results. The friction at the point of tangency is probably so low that hardly any force is imparted to the globe at that point. We agree with Miller that the true direction of pull of an eye muscle probably lies in between the direction of pull that fully rotates with the eye and the direction of pull that remains constant in the orbital frame.

the eye and direction of pull staying constant in the orbital frame) with clinical measurements in a large series of palsy and strabismus operations and found the differences between the two to be small.[16] However, pull at the point of tangency, as in Robinson's original model[2] (Fig. 3, arrow 1), yielded more variable results. This strengthens the conviction that the friction at the point of tangency is so low that hardly any force is imparted to the globe at that point. We agree with Miller[12] that the true direction of pull of an eye muscle probably lies in between the direction of pull that fully rotates with the eye and the direction of pull that remains constant in the orbital frame.

Many other new insights have been implemented in the model that cannot be discussed here in detail. For instance, in the original model many parameters were free, i.e. they were not derived from measured data, whereas in the current model, all parameters have been calculated *ab initio*.

From 1992 onwards all complex motility disorders in our clinic were operated with the help of CSM. During the preoperative discussion with the orthoptist on what to operate the following day, the case was simulated with the model. After trying all surgical solutions we could think of, the one predicted as best by the model was chosen.

For preoperative angles of strabismus, as described below, the angles were taken that had been measured the day before surgery. Angles of strabismus were measured with alternating cover and perspex single prisms calibrated in degrees (Gulden Co., Elkins Park, PA 19117-2097), or with the Variprism (a large-amplitude variable prism for measurement of the angle of squint; Vision Research, PB12011, NL1100AA Amsterdam)[17] for the squinting eye. (Note that for comparison of the results of surgery, simple division of prism diopters by two to convert to degrees is totally incorrect and that prisms must be used that are calibrated with the hind surface of the prism frontoparallel to the patient).[18]

For subjective measurement of the angles of strabismus in nine directions of gaze we use the 'Helmholtz' screen[19,20] at a distance of 2½ meters. The Helmholtz screen, based on the 'directions circles' found by Von Helmholtz in 1910[21] is superior to the Hess[22] or Harms[23] screen because the intersections of horizontal and vertical lines on the Helmholtz screen are projected as perpendicular angles on the retina of the patient, coinciding with the hori-

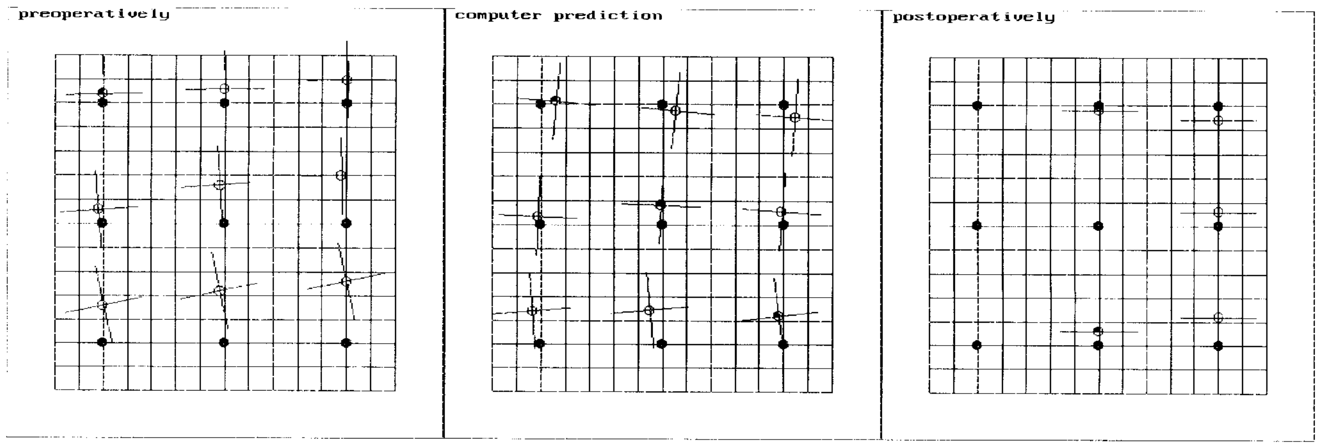


Fig. 4. Preoperative measurements, CSM predictions and postoperative results for Case 1: Left superior oblique palsy treated by a 4 mm recession of the left inferior oblique and a 4 mm tuck of the left superior oblique.

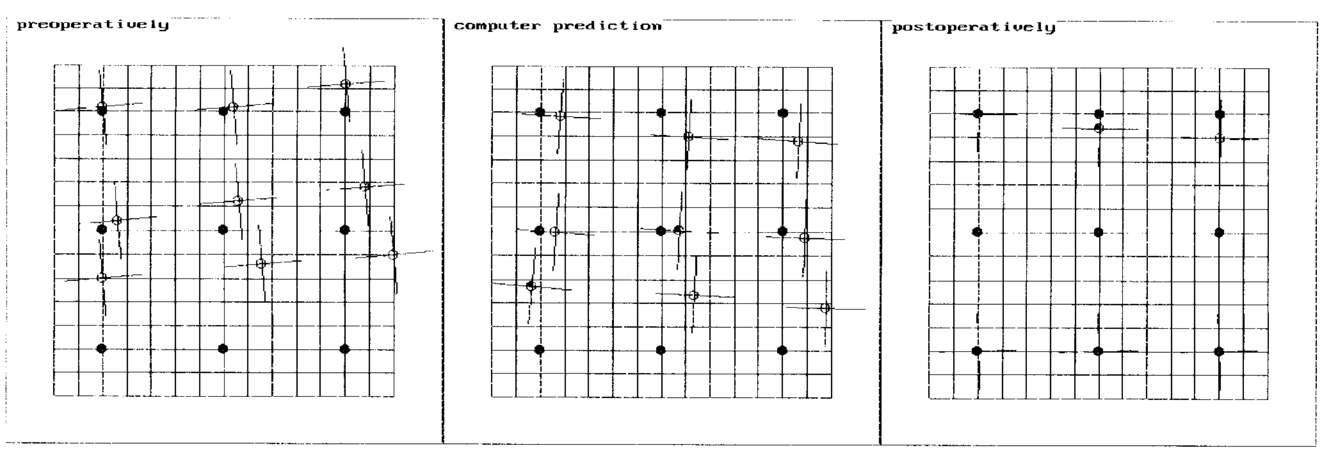
Fig. 5. Preoperative measurements, CSM predictions and postoperative results for Case 2: Left superior oblique palsy treated by a 4 mm recession of the left inferior oblique and a 4 mm tuck of the left superior oblique.

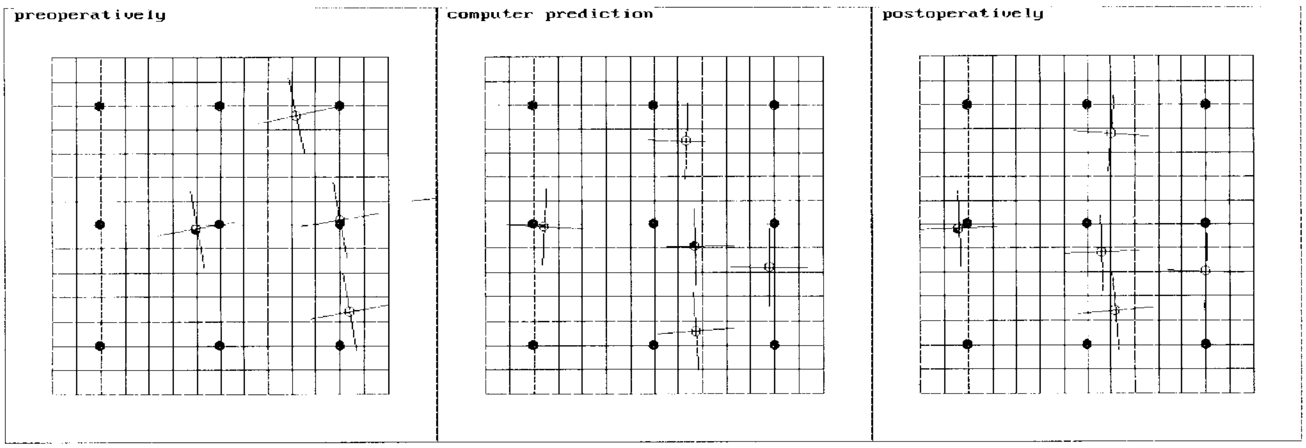
zontal and vertical retinal meridians when cyclotropia is zero, and therefore represent true horizontal and vertical for the patient in tertiary directions of gaze. During the measurements, the patients wore a headband with a small projector that projected a cross on the screen to guarantee 25° secondary and tertiary gaze directions of the fixating eye.

As the postoperative result (as presented in the figures to follow), the measurements were used that were taken three to six months postoperatively. Temporary muscle changes have by then subsided.[24,25] In some cases, only five directions of gaze were available.

Results As said previously, the second program calculates the position of the strabismic eye for nine directions of gaze. From the absolute eye positions the angles of strabismus are derived. These are presented graphically, in a way similar to a Hess chart, together with the preoperative findings presented in a similar fashion. The angles of strabismus are represented by a cross on a rectangular 5° x 5° grid. The cross is tilted in case of cyclotropia, the tilt of the cross being equal to the actual cyclotropia.

To make possible a direct comparison between the predictions of the model and the actual postoperative results, a third chart has been added to the two regular ones in Figs. 4–12. The actual postoperative results are depicted on the right panel, the predictions of CSM are in the middle and the preoperative measurements are depicted on the left. One division equals five degrees. Filled circles represent the position of the fixating, non-squinting





eye, in primary position or 25° secondary and tertiary position. Open circles represent the positions of the squinting eye. In case of perfect alignment the cross may seem missing but actually is covered by the grid. The cases are discussed in detail below.

Fig. 6. Preoperative measurements, CSM predictions and postoperative results for Case 3: Esotropia with a left upshoot in adduction, excyclotropia, diplopia and congenital nystagmus. Recessions of both superior rectus muscles, resections of both inferior rectus muscles and resections of both lateral rectus muscles had been performed previously. She was treated by 5 mm resections of both lateral rectus muscles, a 6 mm recession of the right and a 8 mm recession of the left inferior oblique muscle.

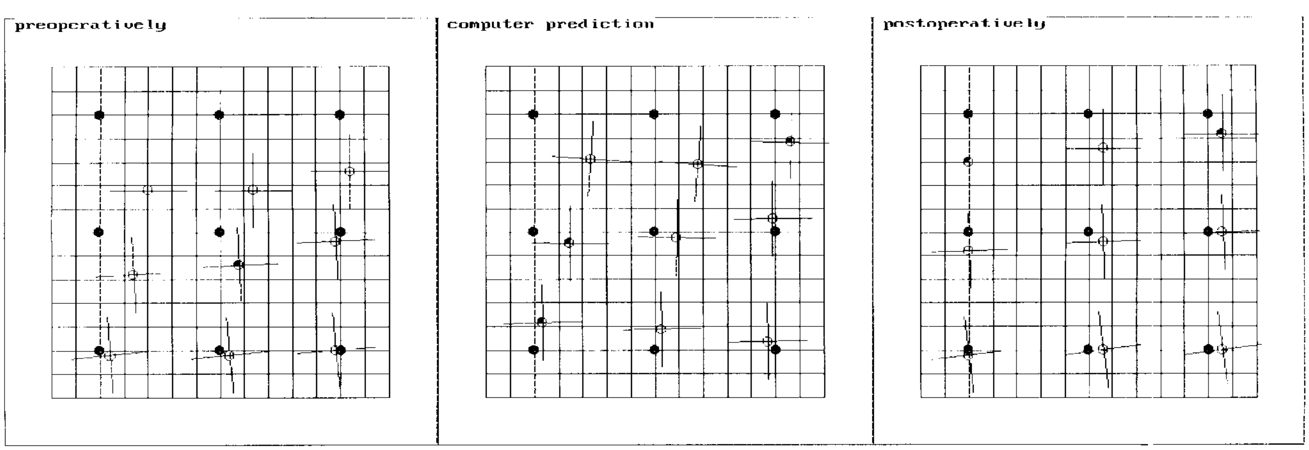
PATIENTS

Case 1 (fig. 4) This 33-year-old man had a left superior oblique palsy. He was treated by a 4 mm recession of the inferior oblique and a 4 mm tuck of the superior oblique of the left eye.

Case 2 (fig. 5) This 32-year-old woman had sustained a head injury several years previously, but had not been referred to an ophthalmologist by her neurologist, although she complained of diplopia. She was found to have a superior oblique palsy and was treated by a 4 mm recession of the inferior oblique and a 4 mm tuck of the superior oblique of the left eye. The postoperative result is better than predicted by the model, possibly because the patient could fuse after surgery.

Case 3 (fig. 6) This 23-year-old woman had an esotropia with a left upshoot in adduction, excyclotropia, diplopia and congenital nystagmus. She had had previous recessions of both superior rectus muscles, resections of both inferior rectus muscles and resections of both lateral rectus muscles

Fig. 7. Preoperative measurements, CSM predictions and postoperative results for Case 4: Partially recovered oculomotor palsy of the right eye after a transnasal hypophysectomy treated by a 4 mm recession of the left superior rectus muscle.



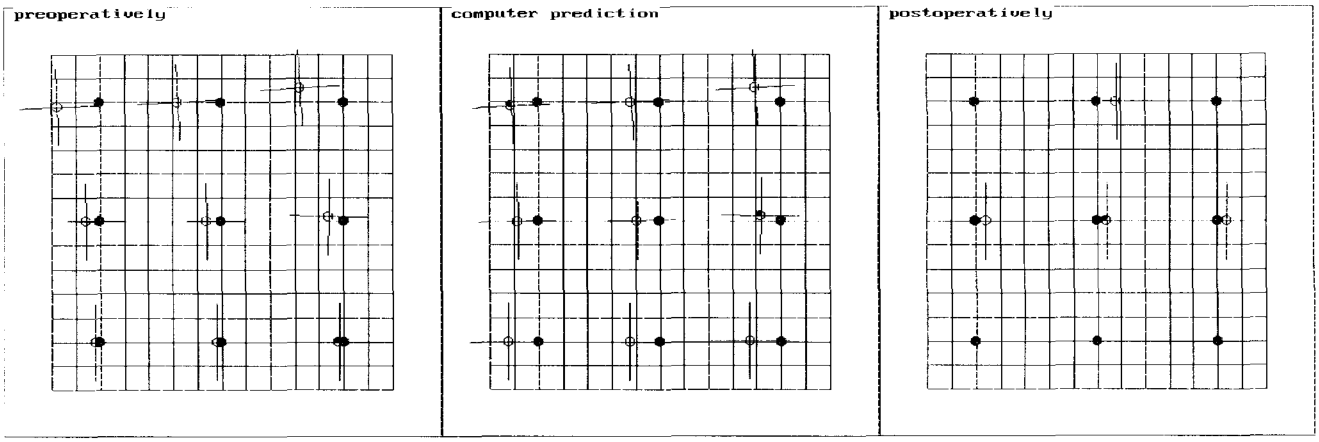


Fig. 8. Preoperative measurements, CSM predictions and postoperative results for Case 5: Small left exophoria with a V-motility, treated by a transposition of both lateral rectus muscles 3 mm cranially.

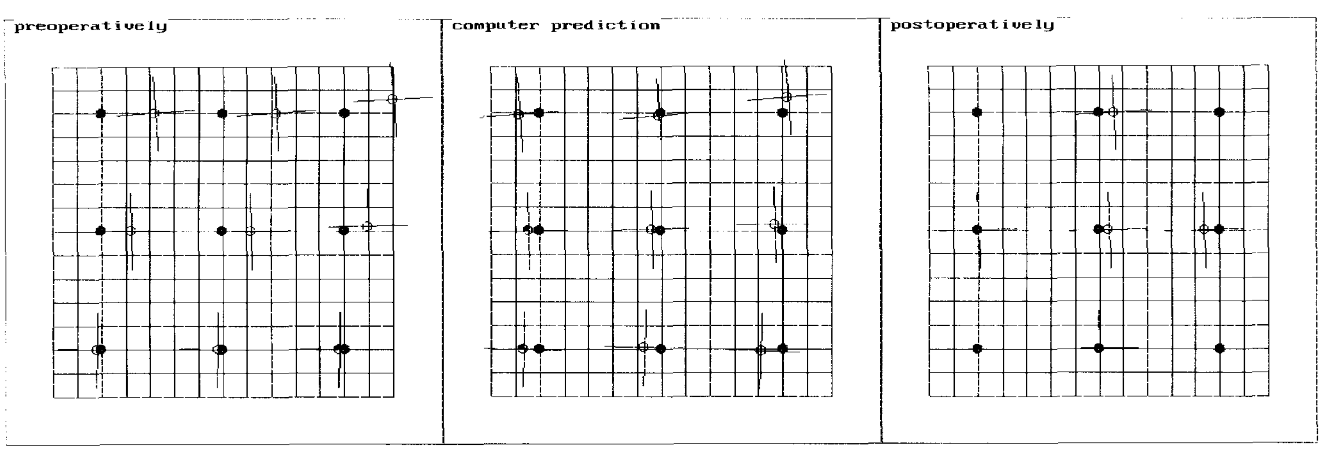
Fig. 9. Preoperative measurements, CSM predictions and postoperative results for Case 6: Right secondary divergent strabismus, previous convergent microstrabismus with nasal eccentric fixation and convergent anomalous retinal correspondence. A recession of the right lateral rectus and tenotomies of both inferior oblique muscles had been performed previously. A 6 mm recession and a 5 mm cranial transposition of the left lateral rectus muscle, and a 3 mm cranial transposition of the right lateral rectus were performed.

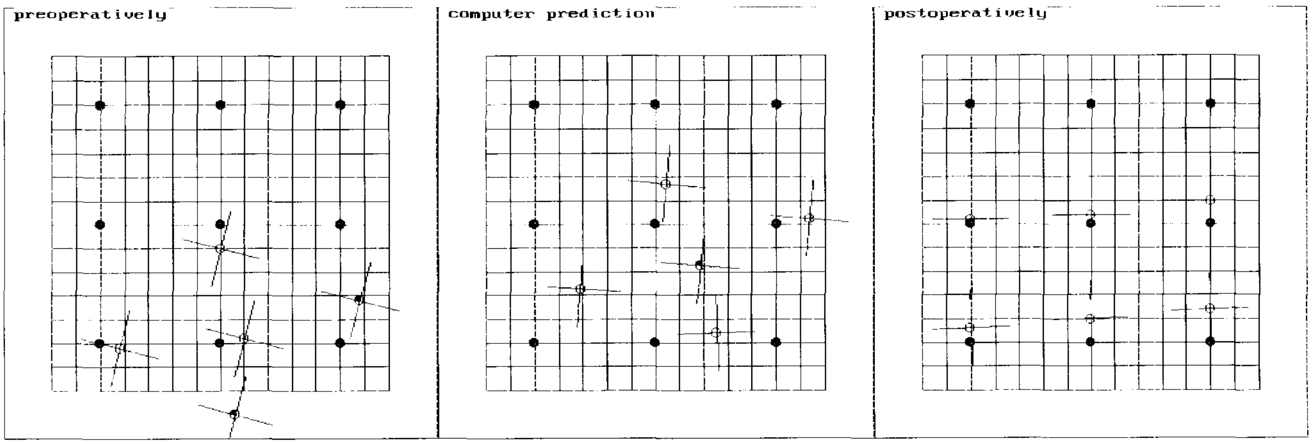
elsewhere. We did 5 mm resections of both lateral rectus muscles, a 6 mm recession of the right and a 8 mm recession of the left inferior oblique muscle. The prediction of CSM corresponds well with the actual postoperative result.

Case 4 (fig. 7) This 65-year-old woman had a partially recovered oculomotor palsy of the right eye after a transnasal hypophysectomy 19 years previously. We did a 4 mm recession of the superior rectus muscle of the left eye. Curiously, the increase of the V-motility that we expected and that CSM had predicted did not occur, possibly because she could fuse after surgery.

Case 5 (fig. 8) This 53-year-old woman had a small left exophoria with a V-motility. Here the model predicted a correction of the V-motility by transposing both lateral rectus muscles 3 mm cranially. We did not add a recession because she had serious diplopia when overcorrecting the exophoria with prisms. In fact, the V-motility was slightly overcorrected, and a small esophoria resulted.

Case 6 (fig. 9) This 26-year-old woman had a right secondary divergent strabismus. Indicative of previous convergent microstrabismus were nasal eccentric fixation and convergent anomalous retinal correspondence. A previous recession of the right lateral rectus and tenotomies of both inferior





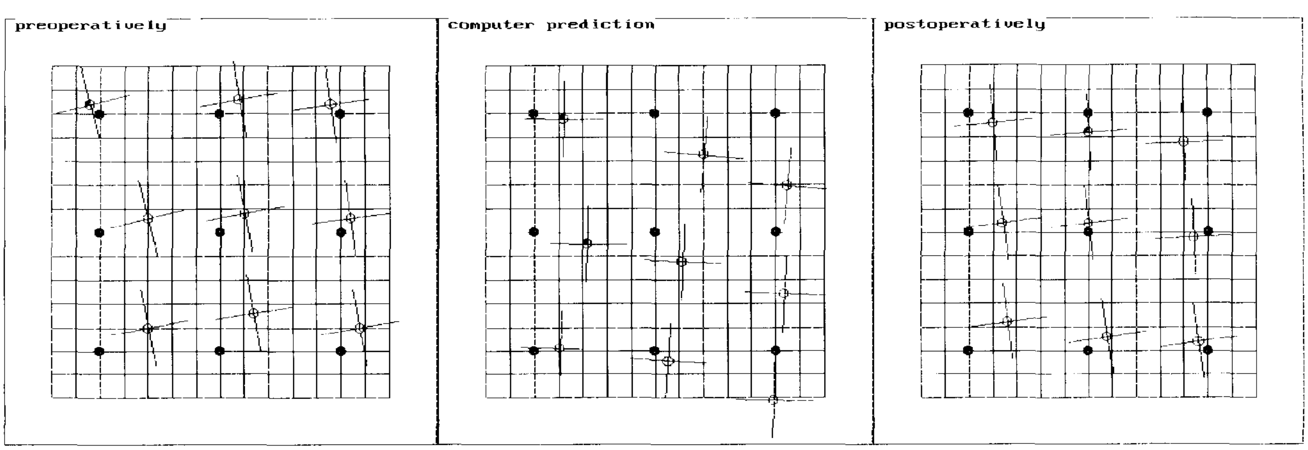
oblique muscles had been performed elsewhere. We did a 6 mm recession and a 5 mm cranial transposition of the left lateral rectus muscle, and a 3 mm cranial transposition of the right lateral rectus. The prediction of CSM corresponds well with the postoperative result.

Fig. 10. Preoperative measurements, CSM predictions and postoperative results for Case 7: Graves' disease with a large hypotropia of the right eye. After a 5 mm recession of the right inferior rectus and a 5 mm resection of the right superior rectus, he was initially undercorrected, but after a few weeks, overcorrected.

Case 7 (fig. 10) This 53-year-old man with Graves' disease had a large hypotropia of the right eye. After a 5 mm recession of the right inferior rectus and a 5 mm resection of the right superior rectus, he initially was undercorrected. He came back after a few weeks, however, with a slight overcorrection of the hypotropia, although motility had now become much more concomitant due to binocular vision. Such late overcorrections in Graves' disease have been seen sporadically by G.H. Kolling (Heidelberg, personal communication) and by me (HJS). At reoperation, the muscle was found at the right place in all cases. Evidently, the contractional state of the muscle that is overcontracting in the initial phase of Graves' disease[26] is altered by muscle surgery.

Case 8 (fig. 11) This 60-year-old woman had had two extensive retinal detachment operations before she was referred to us for alleviation of her excyclotropia. It was planned to do a tenotomy of the left inferior oblique muscle and then to plicate the left superior oblique muscle. The inferior oblique muscle was completely plastered to the globe, however, and a 5 mm plication of the left superior oblique did not alter motility to any large extent.

Fig. 11. Preoperative measurements, CSM predictions and postoperative results for Case 8: Severe excyclotropia after retinal detachment surgery. The inferior oblique muscle was completely plastered to the globe, hence a tenotomy and a 5 mm plication of the left superior oblique did not work.



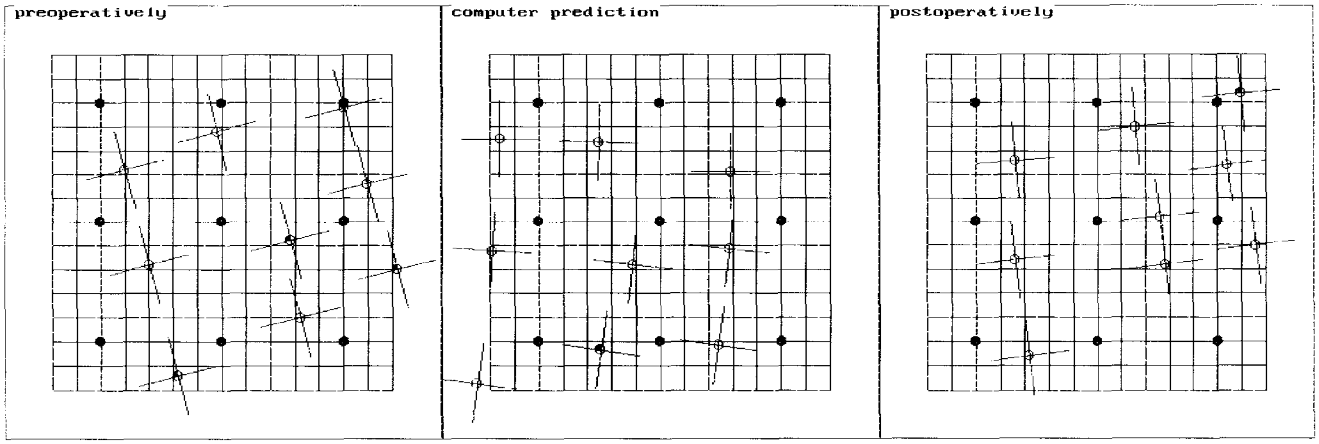


Fig. 12. Preoperative measurements, CSM predictions and postoperative results for Case 9: Comminutive right orbital fractures with a large right hypotropia and a large incyclotropia. 3½ mm recession of the right inferior rectus had been performed previously. Now, 8 mm recessions of both superior oblique muscles were performed.

The prediction of CSM in no way corresponded to the actual result of surgery. In a second operation (not discussed here), the left superior oblique tendon was loosened from scar tissue nasally from the superior rectus insertion, shortened and reattached to the nasal edge of the superior rectus insertion.

Case 9 (fig. 12) This 62-year-old man had suffered comminutive right orbital fractures which had been, by and large, repaired. He presented to us with a large right hypotropia and a large incyclotropia. During a first operation the right inferior rectus was inspected, somewhat loosened out of the scars and recessed 3½ mm. That improved the hypotropia but not the incyclotropia. In the second operation, discussed here, we did 8 mm recessions of both superior oblique muscles in an effort to reduce incyclotropia. As shown here, that had hardly any effect. In a third operation, not discussed here, the insertion of the left inferior oblique muscle was moved cranially and both lateral rectus muscles were recessed.

Discussion In using the model, we found essentially that (i) one does not need CSM for common forms of strabismus, (ii) the model is relatively good in handling complex and unique disorders of motility, and (iii) the model, in its present form, cannot handle cases with mechanical restrictions of motility.

Most conspicuous in this first series of patients operated with the help of CSM is the model's inability to cope with mechanical restrictions of motility (cases 8 and 9). The reason is that the model, in its present form, starts from a normal, average eye and the model does not know what the mechanical properties of the scars are in each individual case. Of course, fibrosis can be modelled in the second of the two programs and theoretically the mechanical properties of the scars could be measured preoperatively in an individual case but, due to the multivariate nature of the problem, such calculation would be prone to error.

CSM, in its present form, is limited in that it only deals with an average eye. In other words, it considers all forms of strabismus as innervational disorders. This limitation also applies to individual anatomical variations, and caution is warranted when these are surmised.

In common forms of strabismus, CSM is not of much help either. The experience of an orthoptist or strabismologist with hundreds or thousands of previous cases with relatively straightforward strabismus problems easily outsmarts the model. It is also possible to model this aspect of strabismus surgery. Rüssmann[27] and Konen and Rüssmann,[28] for instance, developed a BASIC program that derived the relation between angle of squint and amount of surgery from previous cases analyzed by the program. A large number of empirical parameters, like age of the patient and angle of anomalous correspondence, were taken into account. This approach eliminates the influence of systematic errors that arise from different techniques of squint-angle measurement or surgery.

In contrast to common forms of strabismus, the model is good at handling complex and unique disorders of motility. The reason is that a computer solves a complex case just as easily as a simple case, whereas for the human brain, a bizarre combination of vertical and torsional strabismus soon becomes too complex to handle. For instance, if a patient has a downshoot in adduction and A-pattern on the one hand, but an excyclotropia on the other hand, it is very difficult to envision the consequences of an operation, whereas CSM can just as easily predict what will happen.

The two programs are distributed as shareware and can be downloaded from the AAPOS Homepage. The source code of the programs is also available for registered users. The computerized model is distributed in the public domain with the urgent wish that those studying and improving the model will also not commercialize it, to enable research on ocular motility.

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