# Effects of tenotomy on patients with infantile nystagmus syndrome: Foveation improvement over a broadened visual field

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**PURPOSE** To investigate the effects of four-muscle tenotomy on visual function and gaze angle in patients with infantile nystagmus syndrome (INS).

**METHODS** Eye movements of nine patients with infantile nystagmus were recorded using infrared reflection or high-speed digital video techniques. Experimental protocols were designed to record the patients' eye-movement waveforms, pre- and post-tenotomy, at different gaze angles. We used the eXpanded Nystagmus Acuity Function (NAFX) to measure tenotomy-induced changes in the nystagmus at primary position and various gaze angles. The longest foveation domains (LFD) were measured from fitted curves. Peak-to-peak nystagmus amplitudes and foveation-period durations were also measured. All measurements were made unmasked.

**RESULTS** All seven patients with narrow, high-NAFX, gaze-angle regions showed broadening of these regions of higher visual function. Three patients showed moderate NAFX improvement (13.9–32.6%) at primary position, five showed large improvement (39.9–162.4%), and one showed no NAFX change (due to his high pretenotomy NAFX). Primary position measured acuities improved in six patients. All patients had reductions in nystagmus amplitudes ranging from 14.6 to 37%. The duration of the foveation period increased in all nine patients (11.2–200%). The percentage improvements in both the NAFX and the LFD decreased with higher pretenotomy values.

**CONCLUSIONS** In addition to elevating primary position NAFX, tenotomy also broadens the high-NAFX regions. This broadening effect is more prominent in patients who had sharp pretenotomy NAFX peaks. Four-muscle tenotomy produces higher primary position NAFX increases in infantile nystagmus patients whose pretenotomy values are relatively low, with the improvement decreasing at higher pretenotomy values. The tenotomy procedure improves visual function beyond primary position acuity. This extends the utility of surgical therapy to several different classes of patients with INS for whom other procedures are contraindicated. The pretenotomy NAFX can now be used to predict both primary position acuity improvements and broadening of a patient's high-NAFX range of gaze angles. (J AAPOS 2006;10: 552-560)

Surgical therapies for nystagmus have been performed for decades, the Anderson-Kestenbaum procedure being one of the most successful. The main goal of any nystagmus treatment should be to increase the foveation quality, for example, lengthening foveation time, reducing nystagmus intensity, and increasing foveation period accuracy. This goal may be achieved by the four-muscle Anderson-Kestenbaum procedure, which was originally designed to shift nystagmus patients' null regions, thereby straightening head (face) turns.[1-3] The tenotomy procedure emerged from analysis of accurate, objective eye movement recordings in a study of the Anderson-Kestenbaum procedure that showed secondary beneficial effects in addition to the null shifting.[4-7]

Later studies[8-12] provided evidence that tenotomy was effective on human and canine subjects and quickly caught the attention of ophthalmologists, patients, and researchers. With this new technique performed over the past few years, a database of pre- and postsurgical data are being compiled. Previous studies focused solely on the primary position visual acuity evaluation, which is only one aspect of the expected post-tenotomy changes and may be inad-

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equate to measure the total clinical response. The broadening effect, suggested by the Anderson-Kestenbaum procedure data analysis, was not studied. In this study, we used the eXpanded Nystagmus Acuity Function (NAFX), measured at different gaze angles to determine if tenotomy did increase potential acuity across a wider range of gaze angles. Moreover, we categorized types of possible post-tenotomy changes and established criteria for this procedure (when patients should/should *not* have it, how much benefit the patient might expect to receive, etc.). Specifically, our data suggest the need for acuity measures at different gaze angles to better assess the effects of therapy.

## Subjects and methods

### Patient Selection

We restricted our study to the effects of tenotomy on infantile nystagmus syndrome[13] *alone*, eg, patients that had fusion maldevelopment nystagmus or asymmetric (a)periodic alternating nystagmus were not included. The patients studied were considered candidates for the tenotomy procedure if they could not benefit from other known surgical or nonsurgical therapies; they typically came from the following subgroups:

(1) Patients with unchanged nystagmus throughout the whole gaze-angle domain (Patients 3, 4, 7, and 8)
(2) Patients whose damping at near could not be exploited due to lack of stereoscopic fusion (Patients 7 and 8)
(3) Patients with a "null" at primary position (Patients 1, 5, 6, and 9)
(4) Patients with a slight and intermittent "null" which could not be exploited (Patient 2)

To guarantee uncontaminated data, the patients accepted in this study were only treated for their nystagmus, ie, no strabismus surgeries were performed. Patients were informed that the surgery would not straighten their eyes. We now routinely recommend combined strabismus and nystagmus surgery when indicated.

### Recording

Infrared reflection was used for eight patients and high-speed digital video for one. The infrared reflection system (Applied Scientific Laboratories, Waltham, MA) was linear to 20° in the horizontal plane and monotonic to 25 to 30° with a sensitivity of 0.25°. The total system bandwidth (position and velocity) was 0 to 100 Hz. The data were digitized at 500 Hz with 16 bit resolution. The digital video system (EyeLink II, SR Research, Mississauga, ON, Canada) had a linear range of ±30° horizontally and ±20° vertically. System sampling frequency was 500 Hz, gaze position accuracy error was 0.5 to 1° on average, and pupil-size resolution was 0.1% (0.02 mm change in diameter reliably detectable). The data were digitized at 500 Hz with 16 bit resolution. The infrared reflection or Eyelink signal from each eye was calibrated with the other eye behind cover to obtain accurate position information; the foveation periods were used for calibration.

This accurate position data of each eye allows determination of both the smallest amount of strabismus throughout the trial and the fixating eye. Eye positions and velocities (obtained by analog differentiation of the position channels) were displayed on a strip chart recording system (Beckman Type R612 Dynograph, Beckman, Fullerton, CA). Monocular primary position adjustments for all methods allowed accurate position information and documentation of small tropias and phorias hidden by the nystagmus.

### Protocol

This study was approved by the local institutional review board and written consent was obtained from each subject before the testing. All test procedures were carefully explained to the subject before the experiment began and were reinforced with verbal commands during the trials. Subjects were seated in a chair with headrest and a chin stabilizer, far enough from an arc of red light–emitting diodes to prevent convergence effects (>5 feet). At this distance the light-emitting diode subtended less than 0.1° of visual angle. The room light could be adjusted from dim down to blackout to minimize extraneous visual stimuli. An experiment consisted of from 1 to 10 trials, each lasting under a minute with time allowed between trials for the subject to rest. Trials were kept this short to guard against boredom because infantile nystagmus intensity is known to decrease with inattention.

### Analysis

All the analysis was unmasked and done in MATLAB environment (The MathWorks, Natick, MA) using OMLAB software (OMtools, available from http://www.omlab.org). Only eye position was sampled directly; velocity was derived from the position data by a fourth-order central-point differentiator. Position data were prefiltered with a low-pass filter with the cutoff frequency of 20 Hz to eliminate noise without changing the nystagmus signals to be studied. The differentiating and filtering were applied equally to the pre- and post-tenotomy data sets to ensure consistency. Horizontal eye movements were analyzed in all nine patients; vertical eye movements were studied in only one (Patient 4) who had a large vertical component. Analysis was always done on the fixating eye. The post-tenotomy records examined in this study were obtained from 3 to 12 months after the procedure since it was reported that visual functions were stable within this time period.[11]

The NAFX was used to measure tenotomy-induced changes in the infantile nystagmus at primary position and various gaze angles. It is an objective measure of waveform quality and a predictor of potential visual acuity for nystagmus patients assuming that no afferent deficits are present. Because it is a quantitative measure of the direct, eye-movement effects of nystagmus therapies, it is preferred over visual acuity, which is indirect, idiosyncratic, and dependent on many other afferent factors. When combined with pretherapy measured acuity, the NAFX can also predict the improvement in that medically desirable outcome. It could be applied to any nystagmus waveform whose foveation variability (position and velocity) lies within the max-

Table 1. Patient demographics

| Patient no. | Gender/age | Nystagmus waveforms | Primary position strabismus | | Pretenotomy clinical notes | | |
|---|---|---|---|---|---|---|---|
| | | | | | Stereopsis | Preference | Other |
| 1 | F/15 | P, AP, Pfs, Jef, PPfs, DJ | OD | ET3° | >3000” | OS | — |
| 2 | F/21 | J, Jef, DJ | OS | XT6° | 1400” | OD | Slight null at near; weak, intermittent null at left-gaze and up-gaze |
| 3 | M/16 | J, Jef, PC, DJ | OD | XT 10° | 400” | OS | — |
| 4* | F/24 | P, AP, Pfs, J, Jef, PC, PJ, DJ | OS | ET3° | >3000” | OD | Circular, elliptical, oblique nystagmus; impaired color vision; hypoplasia of both optic nerves; bitemporal hemianopic defect in visual field; Demorsier’s syndrome |
| 5 | M/49 | J, Jef, PC | OS | XT3° | 800”-1600” | OD | Frequent direction reversals (Primary position, JL >> JR); JR ≥10° to the right; convergence null |
| 6 | M/28 | P, Pfs, PC | OS | ET4° | 800” | OD | Prior Lasik surgery |
| 7 | F/9 | J, Jef | None | | 200” | None | Frequent direction reversals at all gaze angles |
| 8 | M/6 | P, Pfs, J, PC, PJ, DJ | None | | 50” | OS | Difficulties in gaze holding presurgically |
| 9 | M/15 | J, Jef | OS | XT 15° | 800”-1600” | OD | Near (but not convergence) null; frequent direction reversals at all gaze angles |

*F:* female; *M,* male; *P:* pendular; *AP:* asymmetric pendular; *Pfs:* pendular with foveating saccades; *PPfs:* pseudo-pendular with foveating saccades; *DJ:* dual jerk; *J:* jerk; *Jef:* jerk with extended foveation; *PC:* pseudo-cycloid; *PJ:* pseudo-jerk; *OD:* right eye; *OS:* left eye; *XT:* exotropia; *ET:* esotropia.
*Patient was on gabapentin 300 mg/two times per day on presurgical examination.

imum foveation window of ±6° and ±10°/s. Its use in canine visual acuity assessment was also demonstrated.[14] Five primary position NAFXs for each patient in this study were calculated and averaged; a particularly high or low NAFX was regarded as an outlier and not used. At each gaze angle, two or three NAFX calculations were made and averaged, depending on the data availability. The segments chosen for NAFX analysis avoided blinks and inattention periods. When choosing the segments, we maintained consistency in the pre- and post-tenotomy data sets, that is, the best segments for foveation were chosen, so that the NAFX average would reflect the best potential visual acuity for the patient; this methodology duplicates that used in masked clinical trials.[11,12] Outputs of the NAFX function consist of the NAFX value, foveation time per foveation period, foveation time per second, position and velocity SD in the chosen segment, and position and velocity foveation window size. The first two outputs will be listed and discussed in the Results section. Details about the NAFX may be found elsewhere.[15]

Primary position visual acuities were obtained by the referring physician and recorded in the patients’ clinical notes. Potential visual acuities were provided by the NAFX program as a comparison. Stereopsis was measured with the Stereo FLY and RANDOT Stereo Tests (Stereo Optical Co., Inc., Chicago, IL).

Pre- and post-tenotomy peak-to-peak amplitude in primary position was measured by taking the average of 16 amplitude measurements from different nystagmus cycles. The samples were chosen with the same criteria as described previously for the NAFX analysis.

After obtaining the NAFX values at each gaze angle, second-order polynomial curves were fitted to pre- and post-tenotomy results in Excel. The NAFX percentage improvement (defined by the primary position NAFX improvement divided by the pretenotomy primary position NAFX) was plotted against the pretenotomy primary position NAFX and fitted with a second-order polynomial. The longest foveation domain (LFD) is defined as the range of the gaze angles in which the patient’s NAFX stays above 90% of the NAFX peak value (the NAFX “peak” equivalent to the IN “null”). The LFD percentage improvement (defined as the primary position LFD improvement divided by the pretenotomy LFD) was plotted against the pretenotomy LFD and fitted with a logarithmic curve. If the NAFX versus gaze-angle curve was flat, the LFD was defined as the whole gaze-angle domain where data were available.

## Results

### Patients

The average age of the patients at the time of the surgery was 20.3 (range: 6 to 49; median: 16). Four of the nine patients were female. Six patients were white; two were African American and one was Arabic. None of the patients had previous eye muscle surgery; Patient 6 had a previous Lasik surgery (12 months before). Table 1 shows the age, gender, infantile nystagmus waveforms, and associated pretenotomy clinical conditions of each patient. Pupils, fundus, gross visual field, and slip-lamp examination were all normal unless stated otherwise in the table.

### Direct Outcome Measure—NAFX at Primary Position

NAFX values calculated during pre- and post-tenotomy fixation periods are shown in Table 2, column 3, in which patients are ordered by NAFX improvement. Eight of the nine patients had increases in primary position NAFX

Table 2. NAFX and visual acuity results

| Patient no. | Gender/age | Primary position NAFX change (%increase) [Potential acuities] | Primary position visual acuity change | |
|---|---|---|---|---|
| | | | Visual acuity | Test condition |
| 1 | F/15 | 0.125 to 0.328 (162.4%)<br>[20/115− to 20/45+] | 20/200 to 20/100+1 | OU with correction: 1.25+1.50×134; 1.5+1.00×70 |
| 2 | F/21 | 0.067 to 0.171 (155.2%)<br>[20/215− to 20/85−] | 20/70 to 20/60 | OU with correction: -3.00+3.25×96; −2.75+3.25×89 |
| 3 | M/16 | 0.239 to 0.414 (73.2%)<br>[20/60− to 20/35−] | 20/80- to 20/60+ | OU with correction: -8.00+1.75×60; −7.25+1.75×138 |
| 4 | F/24 | 0.191 to 0.272 (42.4%)<br>[20/75− to 20/55+] | 20/200 OD, 20/400 OS remained unchanged | OU without correction |
| 5 | M/49 | 0.371 to 0.519 (39.9%)<br>[20/45+ to 20/30−] | 20/40+ remained unchanged | OU without correction |
| 6 | M/28 | 0.417 to 0.553 (32.6%)<br>[20/35+ to 20/25−] | 20/60+ to 20/60+2 | OU with correction: 1.00-0.75×178; 1.50-1.25×34 |
| 7 | F/9 | 0.474 to 0.580 (22.2%)<br>[20/30− to 20/25−] | 20/60-2 to 20/60 | OU with correction: -6.00+0.25×78; −6.25+75×141 |
| 8 | M/6 | 0.302 to 0.344 (13.9%)<br>[20/50+ to 20/40−] | 20/60-2 to 20/60+ | OU with correction: -4.00+0.25×30; −4.00+1.50×144 |
| 9 | M/15 | 0.739 to 0.750 (1.5%)<br>[20/20+ to 20/20+] | 20/30- OD, 20/70 OS remained unchanged | OU without correction |

*F:* female; *M:* male; *OD:* right eye; *OS:* left eye; *OU:* both eyes; *NAFX:* eXpanded nystagmus acuity function.

values; the remaining one showed no change. Figure 1 is a comparison of pre- and post-tenotomy primary position fixation data taken from Patient 7, demonstrating greatly improved foveation quality post-tenotomy. Data analysis showed that the foveation periods were extended from 45.6 to 183 ms (301.3% increase). Additionally, the position window was smaller. The velocity window was unchanged; it was already at the lowest value (4°/s). The net improvement in the NAFX was from 0.565 to 0.748, an increase of 32.4%. Given that the *x*-axes have the same scale, it is also evident that postsurgical nystagmus waveforms have lower frequency, consistent with some cosmetic improvement in this case.

## Gaze-Angle Variation

Patients with nystagmus often have "acuity-tunnel vision"; the gaze-angle domain of high visual acuity is often narrow, causing reduced lateral-gaze vision. The NAFX gaze-angle curves showed seven of the nine patients had a narrow peak region. One, Patient 2, with a broad peak, had highly scattered NAFX values, and most of them were lower than 0.1 (<20/200). In her case, the broad peak may reflect a poor curve fit and inferior visual function. The other, Patient 6, who had a flat gaze-angle curve, had a previous Lasik operation.

Patient 1 (Figure 2) is typical in that her lateral-gaze vision was much worse than that for the peak region (in this case between 0° and 5° to the right). Pretenotomy NAFX in primary position was 0.125 and dropped to 0.075 at –15° and 0.039 at 15° (40 and 68.8% decreases). Tenotomy both elevated the primary position NAFX to 0.328 (an increase of 162.4%) and broadened the region of good visual function. Post-tenotomy NAFX stayed at ~0.3 throughout the gaze angles from –15° to 15°; these values were ~140% higher than the pretenotomy primary position NAFX.

Figure 3 shows the NAFX gaze-angle curve for the patient whose primary position NAFX value stayed the same (Patient 9). Despite the absence of an elevation effect, the post-tenotomy curve is much flatter, indicating a broader region in which NAFX is high. At the extremes of the ±15° range, the post-tenotomy NAFX values were approximately 27% higher than the pretenotomy values.

Patient 6, in Figure 4, already had a broad, pretenotomy region of good visual function. The tenotomy procedure elevated the NAFX at each gaze angle without further broadening. The NAFX at primary position was increased by 32.6%, at −25° by 27%, and at 15° by 18%. Overall, pre- and post-tenotomy NAFX gaze-angle curves have similar broad regions of good visual acuity.

## Direct Outcome Measure—Peak-to-Peak Amplitudes and Foveation Period Durations

Table 3 shows the amplitude and foveation-period duration changes induced by the tenotomy. All nine patients exhibited peak-to-peak nystagmus amplitude decreases, ranging from 14.6% to 37%; they also had foveation period increases ranging from 11.2 to 200%.

## Indirect Outcome Measure—Visual Acuity

Column 4 of Table 2 shows the patients' visual acuity changes under the specified testing conditions. Three patients showed more than one line improvement; three showed a few letters' improvement, while Patients 4, 5, and 9 showed no changes in measured visual acuity at primary position. We assume that improvements in visual acuity were due to the surgical procedure and not to age, learning, or change in refractive status.

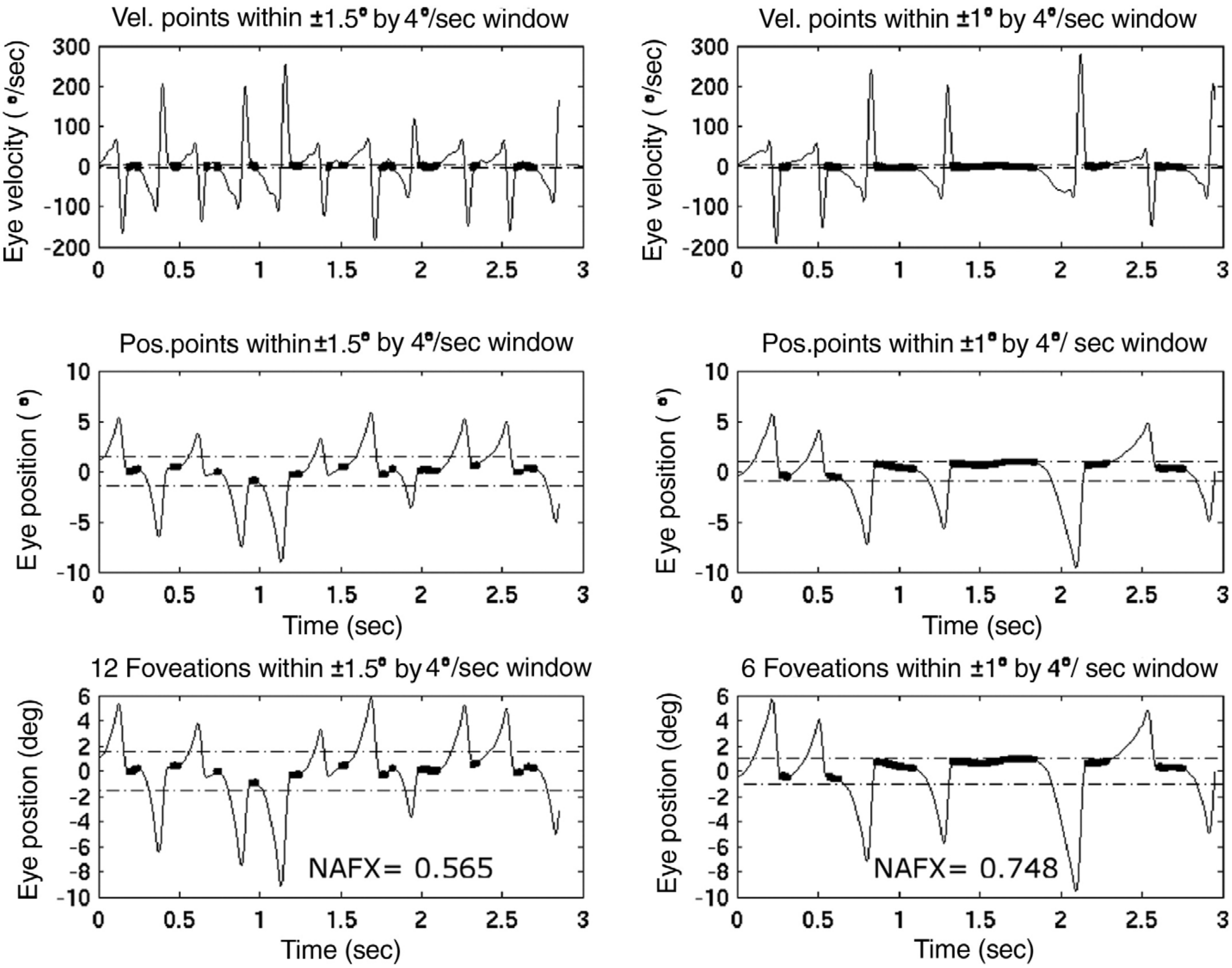

**FIG 1.** Comparison of pre- and post-tenotomy nystagmus waveform from Patient 7. NAFX outputs are presented. Left column, pretenotomy data; right column, post-tenotomy data. Velocity traces (upper row), position traces (middle row), position traces with the NAFX-algorithm-determined foveation periods (lower row) are shown. In each subplot, time periods that satisfy velocity and position criteria for fixation are marked with bold lines. For better visual inspection, pre- and post-tenotomy traces are shown with equal scales. Tenotomy produced the long, flat extended foveation, as seen in post-tenotomy data, which contributed to the NAFX increase.

### Behavioral Changes

Beyond the visual acuity improvement aspect of the procedure, we also observed behavioral changes resulting from tenotomy. Patients 2 and 8 showed improved ability to hold fixation at specific gaze angles. Patients 4 and 5 had strabismus pretenotomy, but post-tenotomy, were able to fuse better so that they alternated fixating eyes.

## Discussion

The effective treatment of infantile nystagmus can best be achieved by distinguishing infantile nystagmus syndrome from other types of nystagmus that appear in infancy, accurately recording patients' eye movements with proper calibration, and quantifying idiosyncratic foveation characteristics that may be exploited to improve visual function. This paradigm is also important for evaluating the effectiveness of new or existing therapeutic procedures.[16] In this study we analyzed the changes in primary position NAFX, foveation time, amplitude, and visual acuity that may be compared with existing studies in the literature. Data were analyzed for individual patients and then grouped to reveal intersubject characteristics.

We do not think the lack of masking was a limitation in this study, since we strictly followed the data analysis procedure (outlined in the Subjects and Methods section) in the two previous masked clinical trials.[11,12] Because the referring physicians performed the clinical portion of this study independently and lateral-gaze visual acuities were not part of their routine clinical examination, that data were unavailable.

Primary position visual acuity is the most routine clinical examination performed. However, in real-world situ-

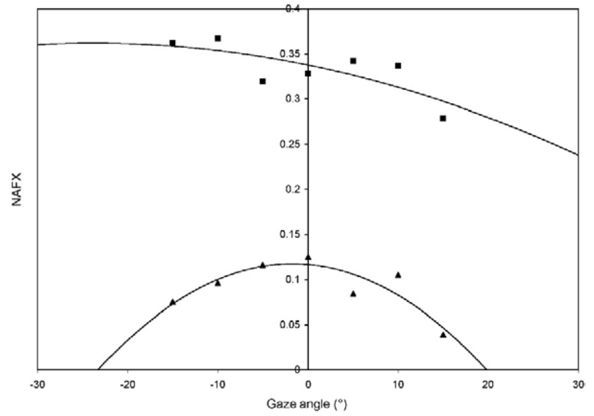

**FIG 2.** NAFX gaze-angle curve of Patient 1 with a sharp peak region pretenotomy and a much-broadened peak post-tenotomy. In this and Figures 3 and 4, NAFX values at various gaze angles were plotted across the gaze-angle domain with triangles denoting pretenotomy data and squares denoting post-tenotomy data. Second-order polynomial curves were fitted for both pre- and post-tenotomy data sets.

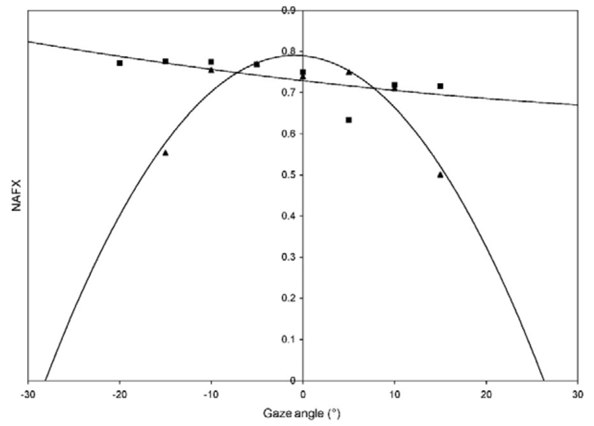

**FIG 3.** NAFX gaze-angle curve of Patient 9 whose high pretenotomy NAFX precluded any further improvement at primary position; this patient exhibited great improvement at lateral angles.

ations the eyes do not remain in primary position. Good lateral-gaze vision could greatly reduce the stress that patients experience when viewing targets without moving their head. Therefore, lateral-gaze vision should be assessed when evaluating surgical effectiveness. The NAFX gaze-angle curves serve this purpose and document the positive effects of tenotomy. The NAFX documentation of better foveation over a broader range of gaze angles was the foundation for recent studies of postsurgical visual acuity improvement at lateral gaze angles.[17] We recommend that surgeons measure visual acuity in lateral gaze before and after nystagmus surgeries to better characterize the effectiveness of surgical interventions for nystagmus.

The pre- and post-tenotomy curves showed three types of improvement: (1) patients with a narrow NAFX peak region had both an elevation in primary position NAFX and broadening effects in lateral gaze (Patients 1, 3, 4, 5, 7, and 8, eg, Patient 1 in Figure 2); (2) patients with a broad peak had an approximately homogeneous elevation of NAFX throughout the whole gaze-angle domain (Patients 2 and 6, eg, Patient 6 in Figure 4); (3) patients who had high pretenotomy primary position NAFX did not have improvement in primary position but did in lateral-gaze vision (Patient 9 in Figure 3). These changes will be discussed and quantified in the following sections.

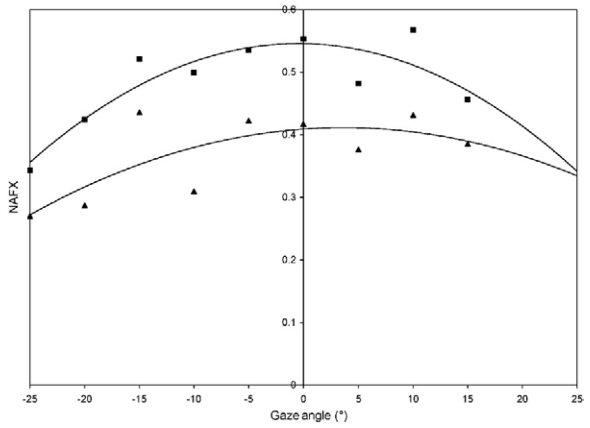

**FIG 4.** NAFX gaze-angle curve of Patient 6 who had broad pretenotomy peak; tenotomy elevated the entire curve without additional broadening.

The infantile nystagmus foveation periods (where the eyes remain at or close to desired fixation with little or no movement) greatly affect visual acuity. The tenotomy-induced foveation improvement is prominent in Figure 1. Although the amplitude of nystagmus was not greatly reduced, the patient was able to foveate the target longer. As is demonstrated elsewhere, nystagmus amplitude alone is not a good indicator of visual function.[15,16,18] The improvement in foveation quality was idiosyncratic, as shown by Table 3. Patient 9 is noteworthy: tenotomy did not produce a large increase of primary position NAFX and this patient had a high presurgical NAFX. Patients with high percentage increases (eg, Patients 1, 2, and 3) also had low pretenotomy NAFX values. This implies that a high pretenotomy NAFX leaves little room for primary position improvement. To quantify this, we plotted the nine patients' NAFX increases versus pretenotomy NAFX values in Figure 5. Equivalent data from the studies by Hertle et al[11,12] and one acquired pendular nystagmus patient were also included.[19]

The NAFX percentage change curve is monotonically decreasing, approaching 0 as the pretenotomy NAFX approaches 1 (highest possible value). For patients ≥6 years old, the curve does not suggest age-dependent effects of tenotomy; it predicts that if we expect to have at least a 20% increase in primary position NAFX, the pretenotomy NAFX should be lower than 0.5. The NAFX provides additional data that may help in surgical decision-making: for the past 10 years, it has been an essential tool in our laboratory for enhancing the therapeutic and predictive relevance of presurgical planning.

Table 3. Tenotomy-induced amplitude and foveation changes

| Patient no. | Gender/age | Pre- and post-tenotomy amplitudes in °p-p (% decrease) | Pre- and post-tenotomy foveation period durations in ms (% increase) |
|---|---|---|---|
| 1 | F/15 | 9.8 to 7.9 (19.8%) | 13 to 39 (200%) |
| 2 | F/21 | 11.6 to 8.5 (26.7%) | 6 to 17 (183.3%) |
| 3 | M/16 | 5.9 to 4.1 (30%) | 26 to 47 (80.8%) |
| 4* | F/24 | LE: 7.9 to 5 (37%)<br>RE: 7.2 to 5.2 (28%) | 17 to 26 (52.9%) |
| 5* | M/49 | LE: 4 to 3.5 (14.6%)<br>RE: 3.7 to 2.7 (27%) | 20 to 57 (185%) |
| 6 | M/28 | 4.2 to 3 (30%) | 35 to 65 (85.7%) |
| 7 | F/9 | 11 to 7.6 (31%) | 41 to 80 (95.1%) |
| 8 | M/6 | 6.1 to 5.1 (16.4%) | 18 to 26 (44.4%) |
| 9 | M/15 | 1.35 to 0.93 (34%) | 119 to 135 (11.2%) |

*F:* female; *M:* male; *RE:* right eye; *LE:* left eye; °p-p, peak-to-peak.

*Patients whose fixating eye alternated; both eyes were examined for the amplitude decrease in these two cases.

Improvement in lateral-gaze vision is indicated by changes in the breadth of the NAFX gaze-angle curve for each patient. Seven of nine patients showed flattened post-tenotomy NAFX gaze-angle curves, supporting our original hypothesis based on the observation of null broadening after Anderson-Kestenbaum procedures. We hypothesized that patients with sharp peak region should have a broader region of good acuity, while patients with preexisting broad peaks should experience a minimal broadening effect. To test this hypothesis, the LFD were measured for each patient; Figure 6 shows the percentage LFD increase versus pretenotomy LFD data from eight subjects (the LFD of Patient 2 could not be obtained due to the shape of the NAFX gaze-angle curve). The LFD percentage change curve is monotonically decreasing, approaching 0 as the pretenotomy LFD goes to 33°. This supports the hypothesis stated above. Thus, the LFD percentage change curve is an additional criterion to predict postsurgical broadening the high-acuity visual field. For patients ≥6 years old, the LFD curve also does not suggest age-dependent effects.

Having large horizontal and vertical eye-movement components, Patient 4 underwent the horizontal four-muscle tenotomy as a first-stage operation. Horizontal eye movement showed a 42.4% increase in NAFX at primary position. Vertical eye movement data were also analyzed, showing no changes in NAFX or amplitude. This suggests that a second-stage vertical tenotomy could be done to further benefit the patient. Based on our experience with a two-stage tenotomy procedure of all 12 extraocular muscles of both eyes of a canine[9] and that of others in patients (especially children), the anterior segment had no ischemic problems if a second, vertical stage were done at a later date (ie, after circulation in the region operated was reestablished). Since there might be some increased risk, the risk-benefit ratio would have to be assessed on an individualized basis. The horizontal four-muscle tenotomy affected only horizontal eye movements, whereas, in a case of acquired pendular nystagmus in a patient with multiple sclerosis, it also damped the vertical component.[19]

Examining the NAFX gaze-angle curve of Patient 3, we found a slight peak at 10° to the right. This property remained the same after tenotomy. At the time of the initial examination, this peak was missed because the changes in waveforms in right gaze were virtually indistinguishable by visual inspection. The tenotomy procedure increased the primary position NAFX by a 73.2% with an 85% broadening of the LFD. This suggests that the absence of head turn does *not* exclude a four-muscle Anderson-Kestenbaum procedure and the patient might have benefited further from shifting the NAFX/visual acuity peak to the primary position.

In Patient 2 the NAFX predicted a lower value of potential visual acuity than actually measured. The NAFX predicts the potential best-corrected visual acuity; measured acuity should be less than or equal to that value. This may be explained by the patient's slight, intermittent left-gaze and upgaze null. The clinical acuity measurement was made with a free head, probably using the patient's preferred rightward and downward head position, whereas we fixed the patient's head in primary position during our recordings. The best NAFX occurred at –15° pretenotomy (0.119) and –20° post-tenotomy (0.226). If we use the NAFX at these gaze angles to make the comparison with the clinically measured visual acuity, the difference is reduced; the NAFX-predicted visual acuity improved from 20/123 to 20/65+. The remaining difference could be explained by the upgaze null, which was not recorded by the infrared reflection system, which was used only for horizontal movements.

Patients 4 and 5 showed no improvement in Snellen acuities despite increases in NAFX values; this was anticipated because of the complex relationship between nystagmus, other sensory deficits, and Snellen visual acuity. Since the improvement of measured acuity is dependent on a number of unpredictable factors, it is necessary to use ocular motility recordings as an objective measurement. The difference between the predicted visual acuity changes from NAFX values and the clinically measured changes could be explained as follows. The NAFX is calculated with the assumption of an intact visual system, which is not always the case with infantile nystagmus patients (eg, Patient 4). As a result, although the foveation

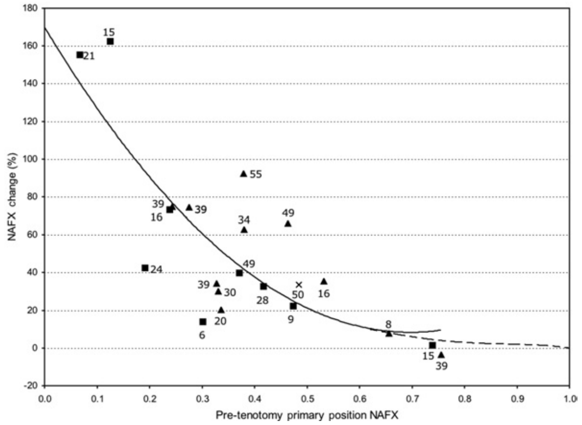

**FIG 5.** NAFX percentage change curve derived from the NAFX percentage change data plotted versus pretenotomy NAFX values. Data from this study are denoted with squares; data from studies by Hertle et al[11,12] are denoted with triangles, and data from one acquired pendular nystagmus patient are denoted with a cross. Data are fitted with a second-order polynomial curve (solid line). Dashed curve is a hypothetical curve if more data from higher pretenotomy NAFX values could be obtained and evaluated. Patient age is indicated by the number near each data point.

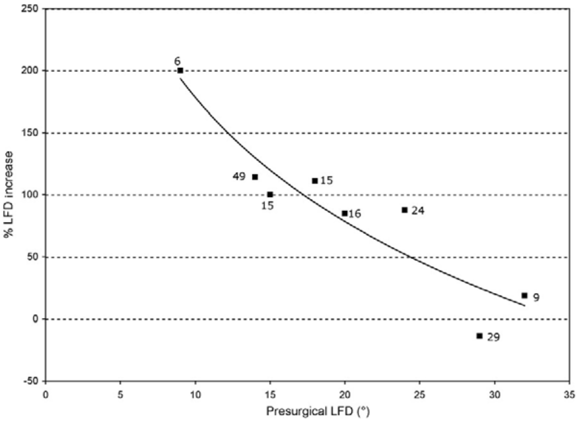

**FIG 6.** LFD percentage change curve derived from the LFD percentage change data plotted versus pretenotomy LFD values. A logarithmic curve (solid line) is fitted to the data points. Patient age is indicated by the number near each data point.

quality might be markedly improved, it is the presence of additional afferent deficits that limits the visual acuity improvement. Additional factors could be patient age, associated strabismus, amblyopia, uncorrected refractive errors, and associated central nervous system disease. Also, since infantile nystagmus is affected by psychological factors, it could have been exacerbated from its baseline level at the time of examinations. Clinical examination differs from daily life experience in that patients may feel stressed by the former; this stress is not only idiosyncratic but also may differ from one examination to the next. Thus, slight improvements in primary position visual acuity due to tenotomy (eg, Patient 5) might not necessarily be reflected in measured visual acuity.[4,11,15]

Tenotomy is a muscle-sparing procedure that presumably does not provoke a confounding central response. In addition to infantile nystagmus, tenotomy has been reported to be effective in other types of nystagmus, eg, asymmetric (a)periodic alternating nystagmus, acquired pendular nystagmus, and seesaw nystagmus.[9,19] Tenotomy has also been reported to reduce oscillopsia.[19] Because each of these types of nystagmus has a different mechanism and putative anatomical site, it is unlikely that tenotomy affects central signals. In Figure 5, data points were included from infantile nystagmus, asymmetric (a)periodic alternating nystagmus, and acquired pendular nystagmus patients and were all fit with the same curve. The coincidence of the data points from this diverse group of patients suggests that tenotomy improves all three types of nystagmus in the same way.

In conclusion, the overall therapeutic effect of four-muscle tenotomy is a broadened area of heightened visual function; patients with more impaired visual function (ie, low pretenotomy NAFX, sharp NAFX-curve angle) have a larger chance of improvement. The tenotomy procedure extends the possibility of surgical therapy to several different classes of patients with IN for whom other procedures are contraindicated, for example, patients who had no NAFX peak, a peak at primary position, or a time-varying peak.[5,10] It could also benefit patients with acquired nystagmus and oscillopsia. The NAFX and LFD percentage change curves are two additional examples of the use of the NAFX to both predict and measure the effectiveness of nystagmus therapies, for intersubject comparison, and planning of therapeutic intervention in infantile nystagmus. Accurate eye movement recording data makes it possible to predict different therapeutic changes using the corresponding percentage-change curves developed in this article. Only patients with *both* a high primary position NAFX (>0.6) and a large LFD (>25°) would not be expected to receive either benefit from tenotomy; all others remain candidates.

The predictive value of both the NAFX and the LFD for infantile nystagmus patients <6 years old should be studied to determine if there may be even greater therapeutic effects during the early stages of ocular motor and visual system development. Future studies should also include tenotomy-induced gaze-angle variation and broadening studies of other types of nystagmus, such as acquired nystagmus. Tenotomy combined with other nystagmus treatments, including drug therapy, strabismus procedures, or refractive (prism) modifications, requires more study. The possibility of chemical/mechanical tenotomy still needs to be assessed. Also, the proprioceptive feedback loop, by which the tenotomy is hypothesized to work, needs to be studied and incorporated into a more realistic model of the ocular motor plant.[20-22]

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