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Neuro-optometry: An Evolving Specialty Clinic*

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ABSTRACT

Neuro-optometry is evolving as an optometric clinical specialty focusing on neurological dysfunctions of the visual system. Initially, we focused upon abnormalities of ocular movements, and our investigations have now broadened to include static and dynamic measurements of eye movements, accommodation, and the pupil
We feel the clinic serves three fundamental purposes: (1) to provide service to the patient, (2) to perform clinical research, and (3) to broaden the scope of the students' clinical experience. Operation of the clinic, technical methods of measurement, the testing protocol, and examples of interesting clinical recordings are described.

Neuro-optometry is now evolving in directions that depend upon the utilization of this specialty clinic in our School of Optometry. We, ourselves, are concentrating on the motor function aspect of neuro-optometry which includes versional eye movements of all types: fixation, optokinetic nystagmus, eye tracking, reading eye movements, and "scanpaths" or free viewing of pictures. We are also studying vergence eye movements and the interaction between vergence and versional eye movements. Furthermore, the triadic response (accommodation, pupillary, and vergence eye movement responses to near and far targets) is another area of our focused attention, and we are making dynamic studies of all these in our Neuro-optometry Clinic.

Sensory functions, such as visual fields or visually evoked responses (VER), are also clearly of great importance and, in fact, are being developed by other faculty members in our school. Another area of increasing importance in neuro-optometry is the fundoscopic study of the nerve fiber layer in the retina, including the remarkable anatomical region of the optic nerve head. Although the importance of this has been emphasized, for example, by Professor William Hoyt who was advocated using a green light in the ophthalmoscope for better viewing of the retinal nerve fiber layer (William F. Hoyt, personal communication), we have not yet introduced this as a procedure in our Neuro-optometry Clinic but are considering a clinical photographic study in this direction.

RATIONALE

The rationale for our Neuro-optometry Clinic with its emphasis on motor dysfunctions is primarily one of service to our patients. *Clinical service* means to us that each patient will be studied *for the direct benefit of the patient.* His optometrist or physician will obtain an objective record of the oculomotor disability to refer to in the chart and the best quantitative evaluation of his disorder to correlate with the clinical evaluation. Eye movement recordings are now an ongoing clinical testing procedure in this clinic and in many hospitals. Electro-oculography (EOG), photoelectric eye movement recordings, and electromyography (EMG) techniques are not "human experimentation" in the accepted sense of these terms. The Committees on Human Experimentation at both the University of California, Berkeley, and the University of California, San Francisco, have carefully reviewed our procedures and have agreed with us

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concerning our rationale of clinical service to the individual patient. Based upon this information, they have allowed us to carry out these procedures without requiring the explicit consent of the patient, since all procedures performed on the patient are for his direct benefit as part of his normal optometric or medical care. The data will be collected as a consequence of established (in California) medical procedures as ordered by the patient's optometrist or attending physician. Such procedures are nonintrusive and present no risk to the patient as defined by the Department of Health, Education and Welfare.

In addition, we expect to do *clinical research* which depends upon detailed analysis of the eye movement records using our on-line laboratory digital computer and other bioengineering and neurological analysis techniques, such as control systems models of the human eye movement system. The purpose of this work is to use "nature's experiments to refine such math-

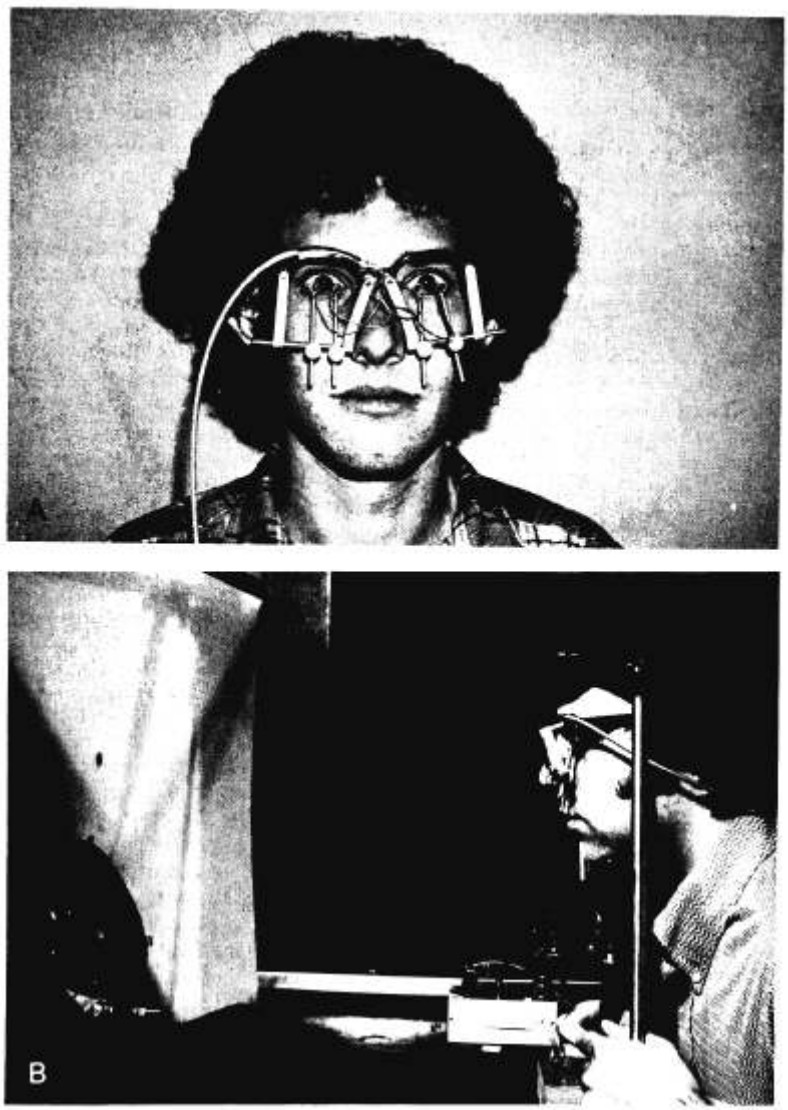

FIG. 1. A, eye movement monitor with binocular photocell sensors mounted on a modified ophthalmic frame in place on patient. Circular photocells positioned approximately 12 mm from the eye and perpendicular to the globe measure amount of infrared light reflected from the nasal or temporal limbus, respectively. B, patient's head supported by headrest and chinrest. The target is a small spot of light moving on a large, translucent screen 57 cm away (on left). Infrared light source (lower left) is a tungsten lamp with a Kodak No. 2 darkroom safelight filter.

ematical descriptions of the neurological control system." This clinical research does not inconvenience the patients, since it is carried out in large part after the patient has left the laboratory and, indeed, after the clinical report has been sent to the referring doctor. The results of our clinical research will appear as case studies[a]:

1. A. T. Bahill et al. on "Dynamic and Static Violations of Hering's Law of Equal Innervation"
2. K. Ciuffreda et al. on "Reading Eye Movements: Case Reports"
3. R. Kenyon et al. on "Absence of Disparity Vergence Eye Movements"
4. S. Phillips et al. on "Dynamic Abnormalities in Accommodation"

These are examples of the output of our Neuro-optometry Clinic.

Our philosophy is that there is really no difference between applied and basic research. Our neuro-optometry studies can contribute in an applied clinical research fashion by helping to define the history of a motor abnormality, including its recession, following treatment; in optometry, treatment may include vision training or corrective lenses. At the same time we are doing basic research, because this information may yield new insights into the underlying neurological mechanisms controlling eye movements which may lead to improved basic bioengineering models of these controlled processes, a very basic research goal indeed.

A final rationale for our Neuro-optometry Clinic is an innovation in the *professional instruction* in the School of Optometry. A newly established section of Optometry 483A,B,C, the Neuro-optometry Clinic, will enable our optometry students to come in contact with patient examinations in our clinic, so that they can become acquainted with this evolving specialty area of optometry. In addition, the objective recordings and quantitative studies of these patients will enable the students to become conversant with this important area of interaction between clinical medicine and clinical optometry.

CLINIC OPERATION

The mode of operation of our clinic over the past year has been to encourage and accept direct referrals from the ongoing clinics in the School of Optometry. Our referrals have come from a number of other specialty clinics: orthoptics, strabismus, pathology, and the general refraction clinic, as well as a scattering of referrals from outside practitioners. As the other clinical instructors on the faculty and the 3rd and 4th-year students, who directly manage the patients, become more familiar with our services and potentialities, we may develop other and more vigorous patterns of referral procedures. The clinic director, Dr. Kenneth Polse, has provided us with several opportunities to discuss our Neuro-optometry Clinic and some of our findings at meetings of the clinical staff, and we have found this interactive feedback to be of benefit to us in many ways, in addition to our primary point of informing others about our clinic.

The output to the referring optometrist or physician from our clinic, at present, is in the form of a written report summarizing the patient findings, based on our studies of the objective recordings and our attempts to correlate these findings with the patient's general clinical findings and laboratory findings from other clinics, such as the VER clinic. It is hoped also that as students take our specialty program, part of their work would be preparing clinical case discussions based upon the patient studies that occurred during their tenure in the clinic.

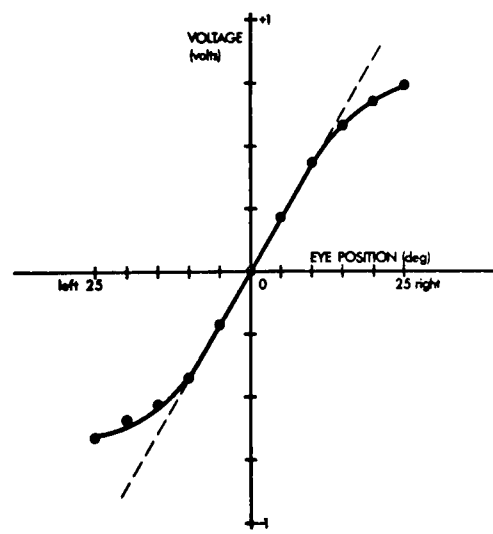

FIG. 2. Plot of eye position versus voltage showing linear operating range of photocell monitor.

[a] A. Terry Bahill, Kenneth J. Ciuffreda, Robert V. Kenyon, and Lawrence Stark, Dynamic and static violations of Hering's law of equal innervation, Am. J. Optom., 53 (12): 798–808, 1976; Kenneth J. Ciuffreda, A. Terry Bahill, Robert V. Kenyon, and Lawrence Stark, Eye movements during reading: case reports, Am. J. Optom., 53 (8): 389–395, 1976; Robert V. Kenyon, Kenneth J. Ciuffreda, and Lawrence Stark, Absence of disparity vergence eye movements, in preparation; S. Phillips and L. Stark, Dynamic abnormalities in accommodation, in preparation; L. Thal, S. Phillips, and L. Stark, Isolated paralysis of accommodation in a young woman, Am. J. Optom., in preparation.

TABLE 1. Overview of eye movement recording methods

Method	Published in[a]	Parameter recorded	Estimated bandwidth (Hz)	Tracking range with ±5% linearity (degrees)	Noise or resolution	Comments	Estimated cost ($) exclud. ing strip chart record- er and ampli- fiers
Non-contact methods for measuring eye movements							
Photography of corneal reflection	Psych. Rev., 1901 (Dodge)	Eye position	100	40	0.5°	One of the 1st published records of eye movements and one of the best	30
Photoelectric	Exp. Neurol., 1975 (Bahill et al.)	Eye position	500	20	Less than biological noise which is ~1 min arc	Used in 2 California clinics; bandwidth usually 70-100 Hz when used with strip chart recorder	
After-image techniques	Treatise on Physiological Optics, 1866 (Helmholtz)	Eye position		100	0.5°	No permanent record	None
Movie camera	Arch. Ophthalmol., 1966 (Higgins and Daroff)	Eye position	32	60		Time-consuming data analysis	30
Stanford Research Institute eye tracker	J. Opt. Soc. Am., 1973 (Cornsweet and Crane)	Eye position	10	~ 12	<biological	Newer version has larger bandwidth but artifacts at end of saccades	30,000
TV type camera	IEEE Biol. Med., 1974 (Merchant et al.)	Eye position	15	60		Also made by Whittaker Corp. and Hamamasu Co.	50,000
Mirror for reflected eye image	Ann. Ocul. (Javal), 1879	Eye position		60	1°	No permanent record	
Contacting methods for measuring eye movements							
Electro-oculography (EOG)	Vision Res., 1970 (Weber & Daroff)	Sine eye position	25	80	1.5°	No head restraint necessary; output varies with ambient light; large amount of drift	25
Contact lens with mirror attached	Science, 1973 (Steinman et al.)	Eye position	60	10	<biological	Also used by Yarbus, Riggs, Cornsweet, Ditchburn, and Fender	3,000
Contact lens with coil attached	Vision Res., 1975 (Collewjn)	Sine eye position	50; could be increased to 1 K Hz	40	<biological	Developed by Robinson (IEEE Biol. Med., 1963)	10,000

TABLE 1—*Continued*

Method	Published in	Parameter recorded	Estimated bandwidth (Hz)	Tracking range with ±5% linearity (degrees)	Noise or resolution	Comments	Estimated cost ($) excluding strip chart recorder and amplifiers
Plaster "contact lens" with lever attached	Am. J. Psych., 1898 (Delabarre)	Eye position	30	15	~0.5°	Cocaine must be used to render cornea insensitive; mentioned for historical purposes only	10

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METHODS

A brief summary of our methods with some illustrative material is presented in order to permit the reader to get a more detailed view of the services that the Neuro-optometry Clinic can provide for the patient. In order to measure eye movements, either versional or vergence, we use spectacle frames with photocells mounted close to the eye, but not interfering with either the patient's eye movements or ability to blink.[1, 2] The pictures in Fig. 1 show a patient wearing these eye movement monitors. When the photo cells are properly positioned and the circuitry is balanced and calibrated exactly as shown in Fig. 2, quite accurate eye movement recordings can be obtained. Appendices A and B give further details on this methodology, and an overview of eye movement recording methods is presented in Table 1. The binocular reading eye movements shown in Fig. 3 are an example of some of the interesting results of our clinical studies.

In order to measure accommodation dynamically, we use a third Purkinje image instrument which was developed by O'Neill and Stark[3] and by Phillips et al.[4] (Fig. 4). The instrument is mounted within a slit-lamp biomicroscope. Because it measures the position of the anterior surface of the lens, it gives only a parametric measure of accommodation; thus, to calibrate, we use a Fincham coincidence optometer based on the Scheiner principle (1619). The Finchman optometer is also used to record static measurements of accommodation (Fig. 5). Here we see the contrast between the response of the normal subject and the response of a patient with difficulty in accommodative facility. Dynamic responses taken with our Purkinje image instrument are shown in Fig. 6. We hope to study the influence of "accommodative rock" vision training procedures in influencing facility difficulties in a selected group of patients in cooperation with J. David Grisham, O.D., Assistant Clinical Professor in charge of the Orthoptics Clinic, and James Ronan, O.D., Clinical Instructor.

Pupillometry has expanded recently to be an

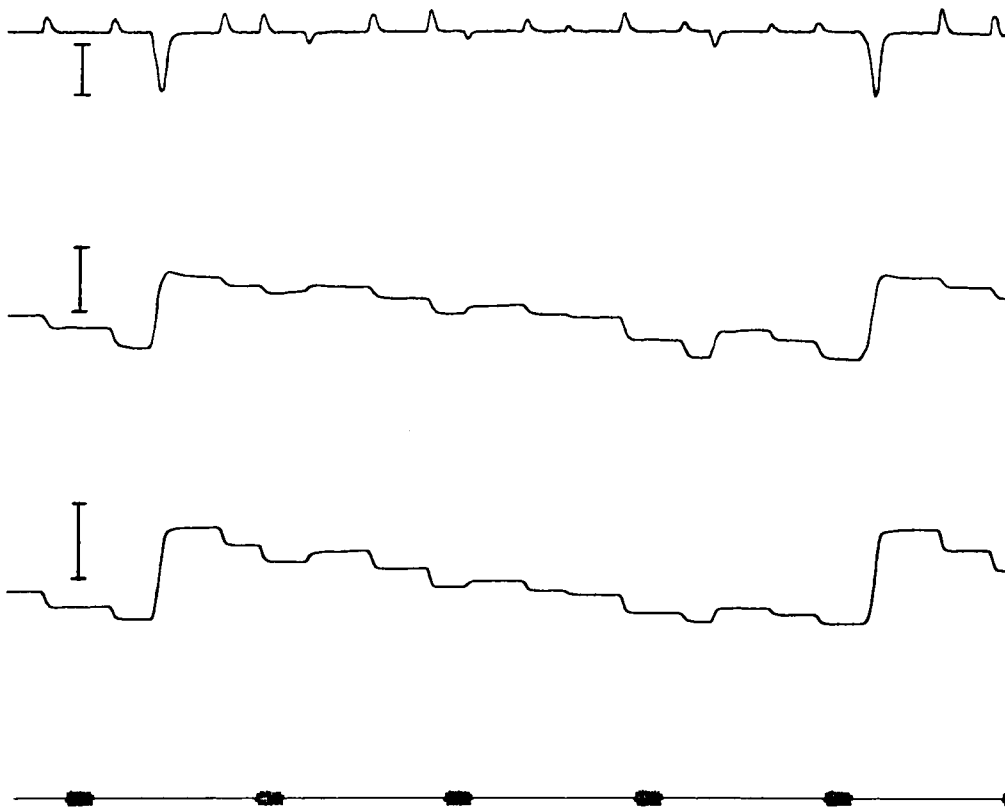

FIG. 3. Binocular reading eye movements of an amblyopic patient showing (from top to bottom) right eye velocity, left eye position, right eye position, and timing trace with 1 sec markers. Upward deflections in position traces indicate leftward eye movements; position calibration bars represent 10 degrees. Velocity calibration bar represents 480 degrees per sec. With the reading card at 50 cm, corrective lenses were not worn; the patient reported seeing reading material clearly. Evident are several regressive movements, glissadic overshooting in the amblyopic eye, and long fixation pauses. The patient's reading rate was reduced to 170 words per minute. Uncorrected visual acuity and refractive error were $+0.75$-2.00×90, 20/38 and -0.50×17, 20/20, respectively, for left and right eyes.

FIG. 4. Essential elements of dynamic optometer, a modified slit-lamp with photomultiplier attached to secondary arm. The instrument measures the amount of light reflected from the anterior lens surface during accommodation, correlating with instantaneous accommodative state. Reflected light (infrared) was amplified by photomultiplier system and signals were recorded. Targets at 100 cm (1.0 D) and 20 cm (5.0 D), shown on adjustable jacks, are alternately presented with temporal randomization to the patient, who is instructed to keep the appropriate target in clear focus. Head stabilization and accurate fixation are a prerequisite for obtaining precise measurements free from movement artifacts. A bite bar may be utilized to minimize head movements; eye movement monitors may be added to determine magnitude of any ocular movement that might have taken place during an experimental run. The eye not being tested is occluded.

exciting area of dynamic study; the TV pupillometer designed by Stark and Troelstra[5, 6] is shown in Fig. 7. Its mode of operation is (1) to obtain a video image of the subject's magnified iris and pupil, (2) to use image-processing electronics to define the pupil-iris border, (3) to

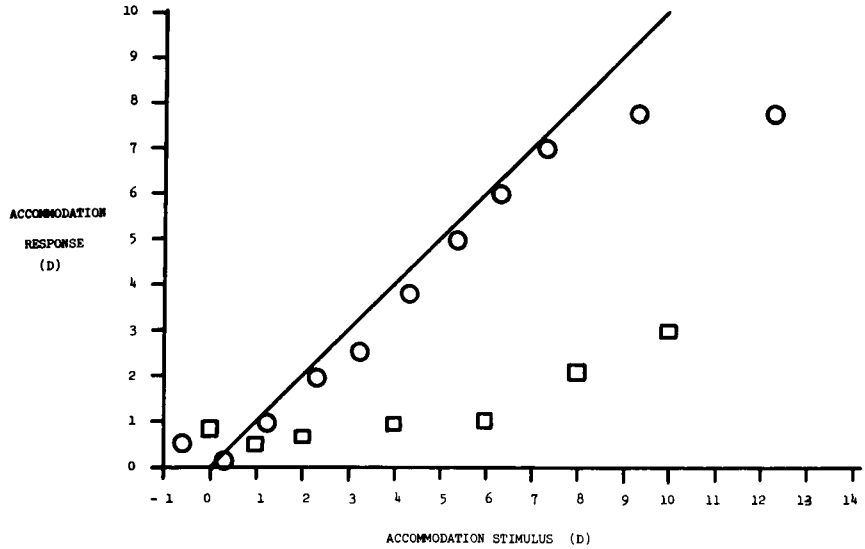

FIG. 5. Two accommodative stimulus-response curves measured with Fincham optometer. Response (O) shows focusing ability of a normal 25-year-old patient. Note that from 0 to 7 D of accommodative stimulus, the patient follows the target quite well and manifests typical "lazy lag of accommodation." Beyond 7 D of accommodative stimulus, the patient approaches the "presbyopic zone" (latent zone), and the plateau gives a measure of accommodative amplitude. In contrast is the response (□) of another 25-year-old patient who complained of focusing difficulties at near and clearly exhibits an impaired focusing ability. At the time of testing, the patient was wearing poorly fitting soft contact lenses and had slightly reduced and variable visual acuity.

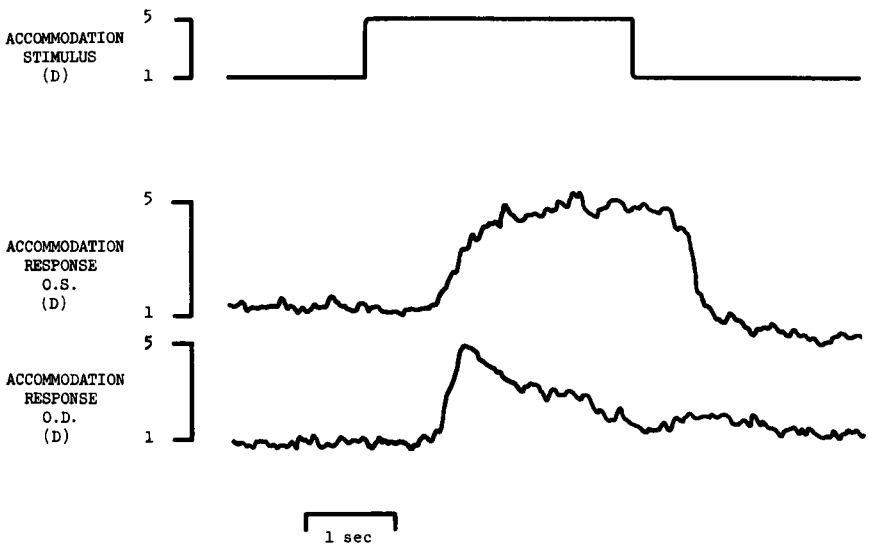

FIG. 6. Dynamic accommodative responses to 4-D step changes of stimulus in a 24-year-old patient who complained of blurred vision and tired eyes after reading or sewing for short periods of time. Both eyes showed a latency of about 750 msec, nearly twice the normal value of about 380 msec. When blur stimulus was presented to the left eye, response amplitude in diopters was within normal limits and without noticeable accommodative drift. When the same stimulus was presented to the right eye, initial response amplitude was normal but accurate focus was not maintained; accommodative response rapidly declined to about 2 D. With continued testing, the patient became slightly fatigued and produced a more variable accommodative response to the same accommodative stimulus. Near the end of testing, with the patient quite fatigued, accommodative response gradually decreased in amplitude; both eyes eventually developed an accommodative spasm centered on 3 D. (Note: static accommodation measurements were within normal limits for age; the Fincham optometer measured an accommodative amplitude of 7.4 D in the right eye and 8.0 D in the left eye; with the Prince rule push-up method using a slowly moving target, measured accommodative amplitude was 9.0 D in each eye.) Each eye was tested separately, and the 2 responses were not recorded simultaneously.

FIG. 7. TV Infrared Pupillometer. On the right are head and chin rest and fixation cross, while on the left are infrared-sensitive television camera, zoom lens, and infrared light source adjacent to the lens. Stimulus is a bright light, seen in Maxwellian view, located within modified slit-lamp illumination housing. Instrument, camera position, and infrared light source are adjusted to obtain a sharp image of the iris on the TV monitor, then the light stimulus is properly positioned. The entire alignment procedure takes 2 min; the clinician is now ready to make accurate recordings of pupillary responses to light, presented in either a pulse or sinusoidal manner, or to step-accommodative stimuli.

mark this border with a white crescent so that the experimenter can be certain that the instrument is functioning (as shown in Fig. 8), and (4) finally, to count the number of TV lines in the pupil image. This count is seen as the dynamic response trace shown in Fig. 9. In this figure, the normal dynamic pupil response is contrasted with the slowed, deficient pupil response of a patient following recent ocular trauma.

PROTOCOL

The testing protocol for the Neuro-optometry Clinic was initially based on earlier experience in various hospital clinics for neuro-ophthalmology. From the protocol (Table 2), one sees that the usual aspects of eye movements, such as fixation, saccadic tracking and smooth pursuit, vergence, reading eye movements, dynamic and static accommodation, and dynamic pupillary responses, are all part of our test. It is important to note that the calibration procedure appears first not only because we begin by calibrating, but also to emphasize the importance of calibration throughout the procedure. Several aspects of the protocol, such as optokinetic nystagmus, and vestibular testing, have not yet been implemented. The accommodation and pupillary tests are sufficiently complex that they are performed at a separate appointment to the clinic.

Once a general overview of the patient's abnormalities is obtained by utilizing the standard protocol of Table 2, it is then possible to do further testing in accordance with a number of special expanded protocols pointing toward spe-

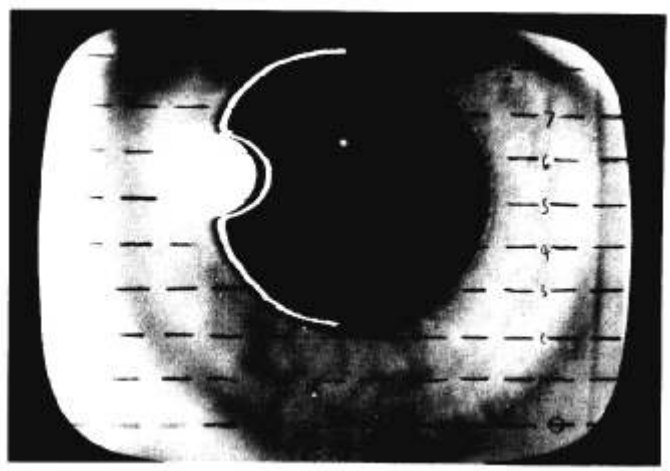

FIG. 8. Patient's pupil and iris displayed on TV monitor. The white crescent seen at the left half of the pupil margin indicates that correct pupillary diameter measurements are being electronically processed; the light spot is the first Purkinje image of light source and does not contaminate pupil diameter measurements; the reference scale in mm is over the monitor screen. Besides using the TV monitor in alignment procedures, a magnified view of the pupil helps verify the record on the strip chart.

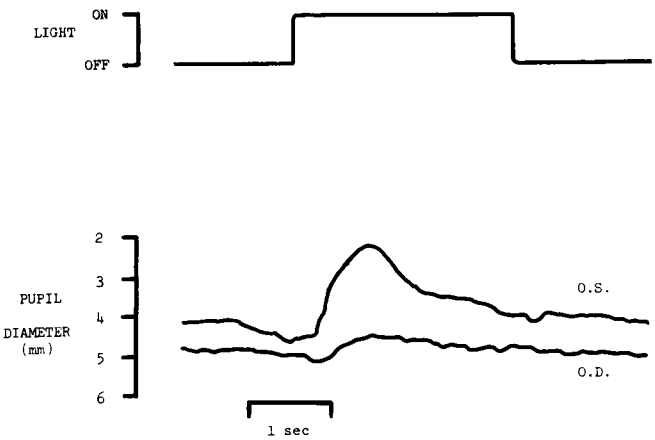

FIG. 9. Light-pupillary response of patient who received a powerful blow to the eye with a baseball 1 week before examination. The left eye exhibited normal pupillary dynamics, with pupillary constriction followed by pupillary dilation, i.e., pupillary escape, during prolonged light stimulation. In contrast, the traumatized right eye had a semidilated pupil (5 mm) and displayed a greatly reduced pupillary response to light, indicating neuromuscular and/or motor fiber damage (N III). Each eye was studied separately, and the 2 records are not simultaneous.

TABLE 2. Testing protocol of Neuro-optometry Clinic

I. Calibration
1) −5° −2.5° 0° +2.5° +5° horizontal steps
2) Triangular target movement (±5°) in the horizontal plane
a. To check for linearity throughout the range of eye movements tested in the protocol
3) −5° 0° +5° vertical steps
a. To check for horizontal-vertical crosstalk
II. Static position
1) Fixation; −5° −2.5° 0° +2.5° +5° horizontal steps
2) Performed with right eye only, left eye only, and with both eyes
a. To test for fixational instabilities, such as gaze or latent nystagmus or unusually large microsaccades
b. To determine whether a composite prism arrangement reduces the amplitude and/or frequency of nystagmus (binocular conditions only)
III. Saccadic tracking
1) −5° to +5° and +5° to −5°
2) 0° to +5° and +5° to 0°
3) −5° to 0° and 0° to −5°
a. To determine saccadic magnitude, latency, duration, and peak velocity
b. To detect violations of Hering's Law to indicate pathological cases
c. To determine the action of drugs or fatigue on saccadic decomposition
d. To detect any abnormal types of overshoot or undershoot
e. To test for the presence of apraxia
f. To test for directional nonlinearities
IV. Smooth pursuit
1) Triangular target movement (±5°) from 0.1 to 1.5 Hz or greater
a. To detect saccades, the velocity is monitored
b. To measure smooth pursuit velocity range and decomposition with increasing target oscillations
c. To measure gain or stability margin
d. To determine smooth pursuit breakdown with auxiliary lenses producing retinal image blur and/or magnification changes

TABLE 2—*Continued*

V. Vergence
1) Targets placed at 50 and 25 cm for testing of divergence and convergence ability
a. To measure peak velocity, latency, and to detect abnormalities in the dynamics of the vergence response for disparity vergence (symmetric, line of sight, general asymmetric) and accommodative vergence
VI. Optokinetic nystagmus: not yet implemented
VII. Vestibular testing: not yet implemented
VIII. Higher level control
1) Reading eye movements; 90-word text for children and 150-word text for adults
a. To detect abnormalities of fixational duration, small saccadic eye movements, large return-sweep saccadic eye movements, fixation frequency (number of fixations per unit text), and reading rate (words per minute)
b. To detect any abnormal reading patterns, such as superimposed nystagmus or backwards reading eye movements
2) Scanpaths: horizontal scanpaths only
a. To investigate patterns of information processing when looking at ordinary scenes and pictures
IX. Accommodation
1) Static accommodation measured with a Fincham coincidence optometer and Prince rule (push-up technique)
a. To detect abnormal accommodative amplitude or accommodative response
2) Dynamic accommodation measured with infrared optometer; targets placed at 100 and at 20 cm
a. To check for abnormally long latencies, slow dynamics, the ability to sustain accommodation accurately, and the effect of fatigue on the accommodative response
X. Pupil
1) Pupilliary responses measured with Stark TV pupillometer
a. To determine the characteristics of the dynamic pupillary response to accommodative stimuli
b. To determine the characteristics of the dynamic pupillary response to step and sinusoidal light stimuli
c. To check for static and dynamic abnormalities relating to neuropathology and ocular pathology

TABLE 3. Patient listing for Neuro-optometry Clinic

Patient no.	Age	Referring clinic	Oculomotor abnormality
12	21	Pathology	Oblique sawtooth nystagmus
26	69	General	Pendular nystagmus; nonconjugate saccades frequently present
29	12	Orthoptics	Jerk nystagmus
35	12	General	Pendular and jerk nystagmus; nonconjugate saccades frequently present
37	8	General	Unilateral vertical pendular nystagmus due to trauma resulting in a blind eye and a pupil unresponsive to light stimuli
10	13	Orthoptics	Slow divergence ability but accommodative dynamics normal
20	30	Orthoptics	Abnormal vergence
11	5	General	Congenital unilateral ptosis but eye movements normal
4	24	Orthoptics	Abnormal vergence eye movements; abducting saccades showed glissadic overshoot while adducting saccades showed glissadic undershoot; these saccadic dynamics are typically found in patients with internuclear ophthalmoplegia (INO); increased accommodative latency and accommodative drift
25	24	General	Poor convergence eye movements; backward reading eye movements (reverse staircase); accommodation slow, reduced range and long latencies
22	22	Strabismus	Abnormal vergence response; fixational instability with amyolyopic eye fixating
9	11	Orthoptics	Poor saccadic and smooth pursuit tracking; hypometric saccades
34	54	Pathology	Hypometric saccades; fixation instability; abduction pseudo-INO (recovered stroke victim)

TABLE 3—*Continued*

Patient no.	Age	Referring clinic	Oculomotor abnormality
6	27	Strabismus	Fixational instability; poor saccadic and smooth pursuit tracking when using amblyopic eye alone
33	22	Strabismus	Poor oculomotor control of amblyopic eye during all eye movement tasks
16	12	Orthoptics	Pseudo-INO; abnormal vergence responses
23	25	Strabismus	Reading eye movements show abnormally long fixational durations and numerous regressions
38	9	General	Reduced accommodative amplitude (<5 D) in each eye; excessive number of fixations per unit text and hypometric saccadic return-sweeps during reading
32	19	General	Accommodative spasm with focus "fixed" for 33 cm and more difficult to relax accommodation than to increase accommodation
41	38	General	INO, but glissadic undershooting of both eyes for adducting saccades only, indicates early neurological involvement; recently diagnosed as having multiple sclerosis

cific disorders. We are developing these as our experience and the case load of our clinic warrants. For example, in a patient with a reading disorder, we might emphasize apraxia tests, laterality of control of saccades, interaction of vergence and version, scanpaths constructed on viewing pictures, and the behavior of the eyes in a number of actual reading tests.

PATIENT EXPERIENCE

Over the past 6 months (to July 1, 1975), we have studied approximately 40 patients. The percentage of patients without clear oculomotor abnormalities was rather high in the early phases of our clinical operation. After establishing communication channels between the clinicians, the senior students, and our own group, the percentage of abnormalities has been greater than 80%. Table 3 lists 20 patients, giving their age, the referring clinic, and the type of abnormality recorded. Our patient population represents a number of interesting oculomotor abnormalities and diagnostic categories: nystagmus, abnormal vergence (strabismus), nonconjugate saccades, adductor lag, and dyslexia. These cases may be further studied and presented as single case reports, as articles describing a diagnostic group, or as articles in some area of control, theoretical, or physiological oculomotor function.

SUMMARY

The Neuro-optometry Clinic exists as a current service in the School of Optometry on the campus of the University of California, Berkeley. Patients are being referred in order to obtain information which the optometrist or physician can utilize for the patient's benefit. The clinic is active in teaching the students, the clinic staff, and, of course, ourselves with respect to the nature of the oculomotor dysfunction definition of syndromes by objective recording, and this results in *more precise diagnosis and better patient management*. In addition to these patient service and teaching functions, we conduct clinical and basic research. Forthcoming research reports explore such areas as dyslexia, Hering's Law violations, and dynamic accommodation and vergence abnormalities.

We quote from the pioneer of eye movement recording, Dr. Raymond Dodge,[7] " . . . I have been able to examine the eye of patients. . . . Some cases presented exceptions to the normal compensatory eye movements, which might, perhaps, become of diagnostic value," and also from our distinguished neuroophthalmology colleague, Dr. William F. Hoyt (personal communication), from the University of California, San Francisco, "Photoelectrical eye movement recording is serving the neuro-ophthalmologist as 'the X-ray' of eye movement disorders."

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zation. However, automatic calibration and computer linearization are of dubious value if they only serve to mask ineffective positioning of the photocells. It is always important to think about photocell positioning and to adjust them for the optimal response.

The *balancing and calibration procedure* includes 3 steps. The 1st step is the independent dark current cancellation of all photocells while the subject is looking straight ahead (0°). The 2nd step is to balance with a potentiometer and to use photocell positioning in an iterative manner. Among the ways to check the balance are to have the subject tract triangular waves and balance for linearity of response, to have the subject make vertical saccades and balance for common mode rejection (with the horizontal set of photocells), and, finally, to have the subject move plus or minus 5 degrees from center (0°) and balance for equality of response. Lastly, the gain which should be independent of the balance, is adjusted so that there is a standard output. For example, in the clinical set up, we have 1 volt equal 1 degree so that we can become accustomed to looking at eye movements on the same amplitude and time scale on the pen recorder.

A different set of procedures might be developed for vertical eye movements, especially if the photocells are arranged so that they sum instead of take differences.

Computer linearization has been developed by 2 groups working on scanpaths: 1 group at Stanford and 1 at Berkeley. In each, the subject positions his eyes over a grid of 9 or 25 dots in a matrix array. The computer measures the voltage output of the photocells about 300 msec after a particular point on the matrix has been brightened as a signal for the subject to direct his gaze at that point. Then the computer develops a linearization algorithm for different pie-shaped sectors of the entire visual field. By using a table look-up, on-line linearization of the eye movement voltage measurements can be performed as data are taken into the computer.

We have been considering automatic calibration procedures for dark current cancellation of both photocells and for balancing the circuitry based on the maneuvers described above. What is needed is a fairly complex measurement and control device, probably a microcircuitry system which would adjust a resistance, such as a FET, whose resistance can be controlled by voltage. This voltage, in turn, would be controlled by some test for zero dark current and for equality of response in the balancing procedure. The computer linearization technique could be done in the first instance with a minicomputer, such as a PDP-8 or PDP-15,but it may be worthwhile to develop a microcomputer for this purpose.

APPENDIX B

We have had extensive experience with 3 types of photocells.

1) The FPT 100 photodiode and the FPT 101 phototransistor, each costing about 1 dollar, have been used in our classroom and clinical laboratory. These have a large field of view and, because of that, are easier to position; however, they are noisier because they take in a good deal of eyelid movement.

2) The LS 400 photodiodes, which cost about 8 dollars each, have a narrow field of view; thus, they are harder to position, but once well positioned, they have the lowests noise level and also the least interference with vision due to their small size. Indeed, Terry Bahill feels that his LS-400 system is not at all limited by electronic noise, and has found eye movement records where all the noise was biological noise.

3) A new type of infrared, light-emitting diode and photodiode system has been on the market for about a year. This is the OPT 125 which costs about 6 dollars. It consists of a small black plastic triangular elment about 1 x 5 x 8 mm, which includes the photodiode and the infrared light-emitting diode in fixed positions. It is the hardest to align, since one must not only carefully arrange it horizontally and vertically, but the distance is also critical, so that the reflecting surface (the limbus) is properly located in the field of view of the emitter and the receiver. An advantage of the OPT 125 is that the light source is mounted on the spectacle frame, and thus, head movement effects are minimized. Another difficulty of the OPT is that they sometimes tend to partially block vision unless carefully positioned.