Velocities of Vertical Saccades with Different Eye Movement Recording Methods

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Voluntary vertical saccades were recorded in five normal human subjects with electro-oculography (EOG), an infrared, limbus tracking system (IR), and a magnetic scleral search coil method. The peak velocity–amplitude relationships of up and down saccades were measured during refixations across the center of the orbit and within the upper and lower fields of the orbit. The search coil was the most accurate method and did not reveal significant differences between the group mean velocities of up and down saccades in the different fields of the orbit. However, subjects can have idiosyncratic differences in velocities between up and down saccades. EOG overestimated the velocities of up saccades. IR underestimated the velocities of up saccades. The search coil was used to record vertical saccades in adduction and abduction. Horizontal eccentric gaze did not significantly affect the velocities of vertical saccades. Invest Ophthalmol Vis Sci 26:938–944, 1985

Voluntary saccades are rapid eye movements that are made when a subject fixates between targets. Contraction of the agonist extraocular muslces produces a sudden increase in force, that is needed to overcome the viscous forces in the orbit and move the eyes rapidly from one target to the other.[1] Peak velocities of horizontal saccades increase in a characteristic manner as the amplitudes increase,[2–6] and velocities of 700 deg/sec or greater have been reported for large amplitude saccades. Maximal recruitment of motoneurons and extraocular muscle fibers occurs during large saccades. Therefore, it would be expected that most disorders that impair the recruitment of motoneurons and muscle fibers or that otherwise interfere with the contraction of muscle fibers will decrease the peak velocity of saccades. In many ophthalmoplegias, the decrease in saccadic velocity can be a more sensitive sign of extraocular muscle paresis than the limitation in range of eye movement or duction. Many reports have documented decreased velocities of horizontal saccades in several supranuclear, infranuclear, myopathic, and orbital disorders of eye movements.

Less is known about the peak velocity–amplitude relationships of vertical saccades in normal subjects and patients than about horizontal saccades. This difference is primarily due to the inability of commonly used eye movement recording techniques to accurately record vertical eye movements. Up saccades with electro-oculography (EOG) have peaked, overshooting trajectories that are probably produced by movement of the eyelids.[7,8] Infrared limbus tracking methods (IR) utilize photocells that are positioned over the limbus nasally and temporally to record horizontal eye movements. The photocells detect the amount of IR light reflected from the surface of the eye. In vertical recordings, the eyelid margins can obscure the limbus superiorly and inferiorly. Collewijn and his colleagues[9] have adapted the magnetic search coil method of Robinson[10] to record eye movements in human subjects. This method is probably the most accurate technique of recording vertical eye movements, but is not widely used in clinical eye movement laboratories.

Leigh and his colleagues[11] used the search coil to measure the relationship of peak velocity and amplitude of vertical saccades. However, the parameters of normal vertical saccades have not been adequately studied with the search coil, EOG, or IR method. For example, it is not known if the velocities of up and down saccades are similar and what effects position in the orbit have on the velocities of vertical

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saccades. The purpose of this study is to measure the peak velocity–amplitude relationships of vertical saccades in normal subjects with the EOG, IR, and search coil methods in different fields in the orbit.

Materials and Methods

Voluntary vertical saccades were recorded in five normal, young adults. Their ages ranged from 22 to 37 yr. No evidence of ophthalmologic or neurologic disorders was found. Informed consent was obtained prior to entry into the study. With DC electro-oculography (EOG) Ag–AgCl skin electrodes were placed immediately above the eyebrow and below the inferior rim of the orbit. Detailed information about the EOG system has been reported previously.[4,5,12] The noise level of the position signal for monocular recordings was 0.2–0.4 deg (rms). Electronic, analog filtering of the EOG signal was used to remove high frequency noise that made identification of saccades by the computer algorithm difficult. For example, digital differentiation of the unfiltered EOG position signal resulted in noise of approximately ±50 deg/sec in the velocity channel. An analog, low-pass filter of 42 Hz was used. The analog signal was then digitized at 200 samples/sec. The data were then differentiated using a two-point central difference algorithm. According to Bahill and his colleagues,[13] such an algorithm is equivalent to an ideal differentiator in series with a low-pass filter of 44.3 Hz.

The analog and digital filtering underestimated the peak velocity of saccades. Two methods were used to determine the degree of this inaccuracy. The EOG position signal of a normal subject was not filtered by an analog filter and was digitized at 1000 samples/sec. Saccades of varying amplitudes were recorded and stored as digitized files. The two-point central difference algorithm at this digitization rate was equivalent to a low-pass filter of 221.5 Hz. Peak velocities were calculated. The digitized position data were then passed through the 42 Hz analog filter, redigitized at 200 samples/sec and used to calculate peak velocities. Filtering underestimated the peak velocity of 10 deg saccades by 6.7% and that of 35 deg saccades by 1.2%. Accurate estimation of the peak velocity of a saccade recorded without an analog filter can be difficult because of a relatively high level of noise in the velocity channel (±50 deg/sec). A function generator was used to produce sine wave signals with amplitudes and peak velocities similar to those of saccades of varying size. These signals were digitized with and without the 42 Hz analog filter, as in the first method. The analog filtering underestimated the peak velocity of 10 deg signals (peak-to-peak) by 2.3% and that of 35 deg signals by 0.6%.

The infrared limbus tracking method (IR), described by Jones,[14] was used. In this method a spectacle-mounted, IR light illuminated the surface of the eye, and photoelectric cells were placed in front of the nasal limbus and temporal limbus. The receptive fields of the photoelectric cells were rectangular in shape. They were centered about the horizontal meridians of the limbus and were tilted such that the superior ends were intorted approximately 45 deg from the vertical meridians. With this configuration, signals from the photoelectric cells were subtracted to record horizontal eye movements and were added to record vertical movements. The IR system had a signal-to-noise ratio of 0.1 (rms) and used a low-pass, analog filter of 0–100 Hz. The signal was digitized at 200 samples/sec, and the two-point central difference algorithm was used to calculate peak velocities.

A magnetic scleral search coil system was used, that was based upon the system described by Robinson[10] and modified by Collewijn and his colleagues.[9] The diameters of the pairs of horizontal and vertical induction coils were 3 ft. The fine wires of the detection coil were imbedded in an annulus of soft plastic, contact lens material (Skalar). The scleral contact lens was placed on the eye after proparacaine had been instilled topically. A low-pass, analog filter of 1 kHz was used. The position signal was digitized at 200 samples/sec, and the two-point central difference algorithm was used to calculate peak velocities. The linear range of this system is ±20 deg. Collewijn and his colleagues[15] have recently described a revolving magnetic field–search coil technique that has linearity better than 1% over 360 deg.

Subjects were seated 1 m from a curved screen. During recordings with EOG and IR, the head was stabilized with braces that supported the forehead and occiput. During recordings with the search coil, a plastic helmet that supported the forehead, malar eminences, and occiput was used. Two-deg diameter dots were placed at the center of the screen and at 5-deg intervals upward and downward, and the screen was centered in the subject's visual field. Relatively large targets were used since the scleral contact lens can blur vision. Spectacle corrections for refractive errors were used. Subjects were instructed to perform three patterns of refixations. In the walk-up pattern they were asked to refixate from the center dot to the dot located at 5 deg in the upper field, back to the center dot, to the 10-deg dot, back to the center dot, and to successively eccentric dots until the 35-deg dot had been reached. Up and down saccades were

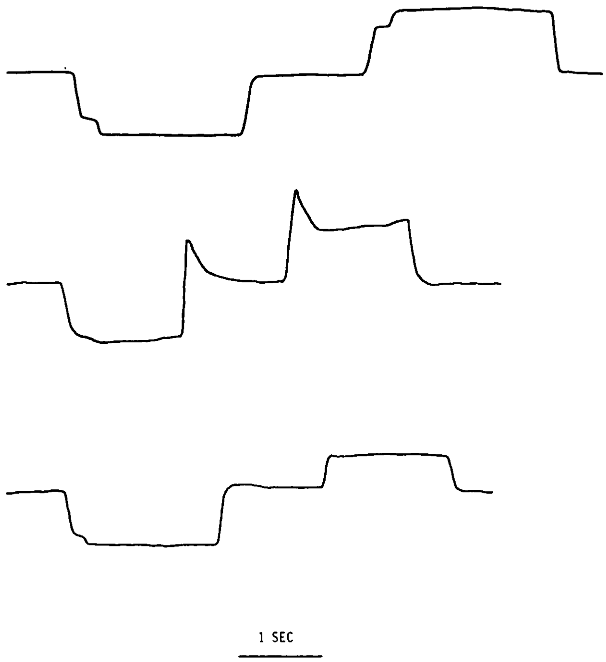

Fig. 1. Trajectories of vertical saccades. Refixations were between fixed targets at center, 15 deg down and 15 deg up. Eye position tracings were made from curvilinear polygraph recordings. Deflections up are upward and down are downward. *Top,* Search coil. Note slight hypometria (undershooting) and corrective saccades to eccentric targets. *Center,* EOG. Note peaked waveform of up saccades. *Bottom,* IR. Note asymmetry of amplitudes of up and down saccades.

made entirely within the upper field of the orbit in this pattern. In the walk-down pattern, refixations were made between the center dot and the dots in the lower field. Up and down saccades were made within the lower field. In the last pattern, refixations were made between corresponding dots in the upper and lower fields. Up and down saccades were made across the center of the orbit.

During recordings with EOG and the search coil, the three patterns of refixation were performed with the eye centered horizontally in the orbit, with the eye in 30 deg of adduction and with the eye in 30 deg of abduction. During recordings with IR, the eye was centered horizontally in the orbit. Vertical eye movements could not be recorded with the eye in adduction or in abduction. Subjects were continually encouraged to remain alert. If evidence of slowing of saccades was observed in the polygraph recordings, subjects were considered to be mentally fatigued and the test was repeated.

Results

Search Coil Method

Calibration factors (computer counts/deg) were calculated for 10-deg intervals (center to 10 deg, 10 deg–20 deg, 20 deg–30 deg) in the upper and lower fields in the orbit. Calibration factors were not significantly different in the first two 10-deg intervals. These observations were consistent with a linear range of approximately ±20 deg based upon theoretical calculations. Robinson[10] estimated that the position signal, which is derived as a sine function, will differ from the true eye position by less than 2% for rotations of less than 20 deg. However, in two subjects the calibration factors in the 20 to 30 deg interval in the upper field were 20–40% greater than in the first two intervals. This large difference cannot be explained by the theoretical nonlinearity of the recording method. It was probably due to restriction of the contact lens' movement by the superior fornix of the conjunctiva. Restriction would be expected to vary among individual subjects, depending upon the size of the superior fornix, and would produce erroneously high calibration factors.

For all recording methods, when a saccade was made within a region of the orbit in which the 10-deg interval calibration factor was different from that near the center of the orbit, the former calibration factor was used to calculate velocities. For saccades crossing the center of the orbit, the average calibration factor of 10-deg intervals above and below the center were used.

For clarity, the directions of vertical saccades will be designated as "up" and "down." The fields in the orbit in which vertical saccades move will be called "upper," "lower," and "across center." Eye movement recordings of saccades from the center of the orbit into the upper and lower fields with the search coil are shown in Figure 1 (top line). No artifacts were found in the trajectories during the three refixation patterns.

Graphs of peak saccadic velocity vs amplitude for one subject are shown in Figure 2. The data points represent individual saccades. Data from search coil recordings during refixations across center are shown on the bottom line. Each point represents the peak velocity of an up or down saccade. The curved lines represent the group mean ± 1 SD for horizontal saccades of normal subjects in our laboratory recorded with bitemporal EOG. There was no difference in velocities between up and down saccades in this subject, and the velocities of vertical saccades were within the normal range for horizontal saccades with EOG.

Figure 3 presents the peak velocity vs amplitude relationships using the group means ± 1 SD. Refixations were within the upper field in the top line, within the lower field in the middle line, and across center in the bottom line. Data from search coil recordings are shown by open circles. With the search coil, up and down saccades had similar velocities in all fields in the orbit. There were no significant differences in velocity of up and down saccades in the three refixation patterns, using the Students t-test for paired observations ($P > 0.05$). The group means, ranges, and differences in peak velocity between up and down saccades across the center of the orbit are shown in the Table 1. An important observation was that a difference in velocities between up and down saccades, calculated as (up − down)/[(up + down)/2], of 20% can be found in a normal subject with the search coil. However, there was no consistent pattern in which velocities in one direction were greater than those in the opposite direction among the subjects.

Adduction and abduction of 30 deg did not significantly affect the peak velocity–amplitude relationships in the three refixation patterns. Student's t-tests for paired observations were performed between up saccades of the same amplitude across the three patterns, between down saccades, and between up and down saccades. No significant differences between group means were found.

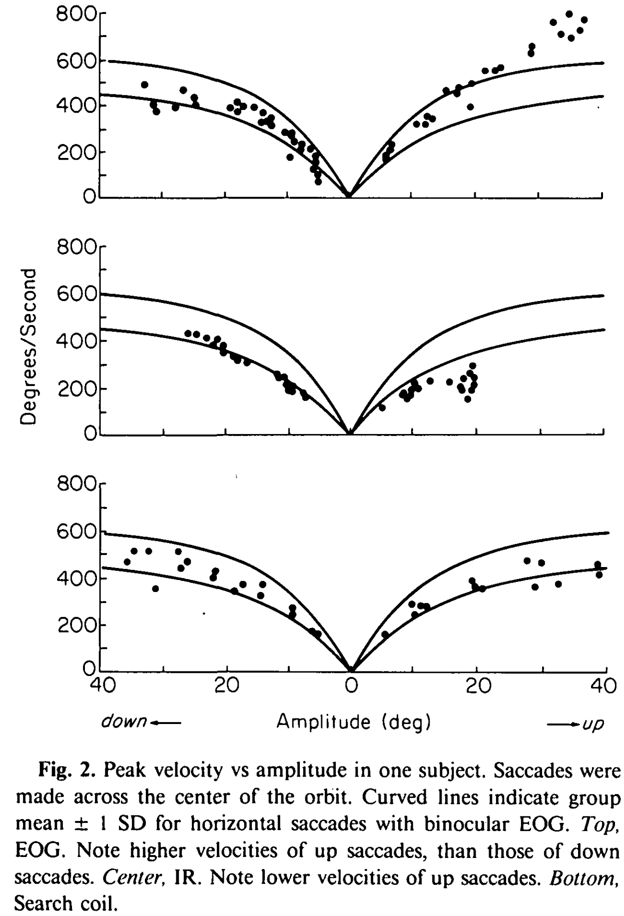

Fig. 2. Peak velocity vs amplitude in one subject. Saccades were made across the center of the orbit. Curved lines indicate group mean ± 1 SD for horizontal saccades with binocular EOG. *Top,* EOG. Note higher velocities of up saccades, than those of down saccades. *Center,* IR. Note lower velocities of up saccades. *Bottom,* Search coil.

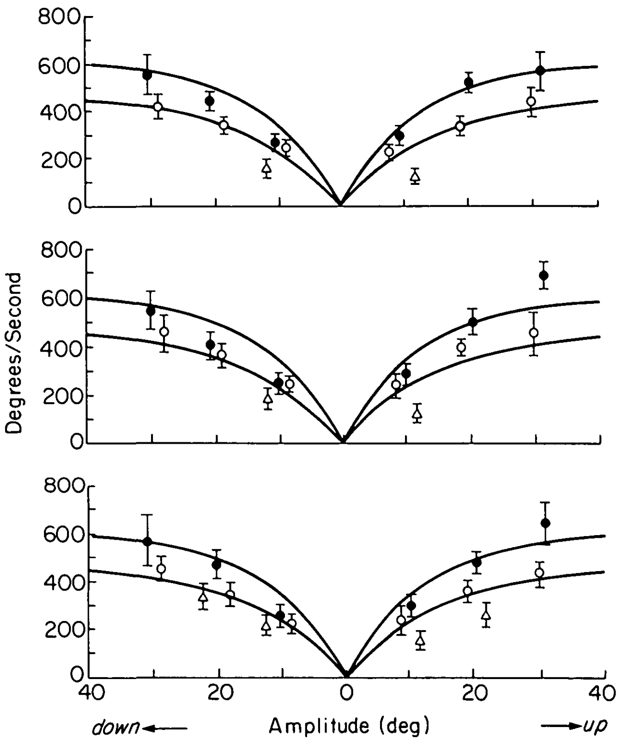

Fig. 3. Peak velocity vs amplitude in different fields of orbit. Group means ± 1 SD are shown. Closed circles: EOG; open circles: search coil; triangles: IR. *Top,* Saccades within upper field. *Center,* Saccades within lower field. *Bottom,* Saccades across center.

Electro-oculography

Artifacts from eyelid movements had major effects on trajectories and peak velocities of saccades. Up saccades had peaked, overshooting trajectories, as illustrated in Figure 1 (middle line). The extent of the artifact, judged as the amplitude of the peak above the sustained position signal following the peak, varied between the subjects and varied somewhat between saccades of similar size in the same subject. Calculation of calibration factors demonstrated that the linear range of EOG was extremely limited. In subjects with large artifacts, the up calibration factor (eye positions judged as the steady position signals before and after the refixation and peaked artifact) was greater than the down calibration factor for 10- and 15-deg intervals. Using the position signal at the peak of the overshooting artifact did not equalize the up and down calibration factors.

The peak velocities of up saccades were consistently greater than those of down saccades. In Figure 2 (top line—EOG recording), the peak velocities of 30 deg up saccades were about 300 deg/sec greater than those of down saccades of the same size. The velocities of 30 deg up saccades with EOG were about 200 deg/sec greater than those of up or down saccades with

Table 1. Peak velocities of vertical saccades across center of orbit

	Saccades					
Methods	*10 deg Up*	*10 deg Down*	*20 deg Up*	*20 deg Down*	*30 deg Up*	*30 deg Down*
Search coil						
mean*	258	237	370	349	443	436
SD†	50	32	34	78	61	48
range‡	144–250	190–269	319–393	234–408	355–479	388–498
mean % diff§	16		10		9	
range % diff‖	3–19		3–20		0–19	
EOG						
mean	323	270	530	409	709	557
SD	34	50	71	70	42	94
range	290–373	221–341	408–581	330–491	657–752	445–663
mean % diff	19		23		21	
range % diff	3–40		15–31		3–31	
IR						
mean	164	215	294	361		
SD	36	21	49	36		
range	104–193	185–238	220–359	313–402		
mean % diff	24		18			
range % diff	4–56		4–37			

* Group mean deg/sec.
† Standard deviation deg/sec.
‡ Range of velocity deg/sec.
§ Mean percent difference between velocities of up and down saccades.
‖ Range percent difference between velocities of up and down saccades.

the search coil (bottom line) in the same subject. As shown in Figure 3, the velocity differences were present in all fields in the orbit. As shown in Table 1, differences as great as 40% between up and down saccades with EOG were found. The differences between the group means were not significant at the 0.05 level for 10-deg saccades, but were significant at the 0.01 level for 20- and 30-deg saccades.

Different calibration techniques were used in an attempt to reduce the differences in velocities. The eye position in 10- and 15-deg upgaze was taken as the steady position signal at the peak of the overshooting artifact or after the artifact, as described above. Separate calibration factors were used for up and down saccades. These techniques reduced the differences in velocity only slightly. Mechanical immobilization of the eyelids with cotton-tipped applicators decreased the size of the peaked artifact and decreased the peak velocities of up and down saccades. However, the differences between the velocities of up and down saccades were not decreased.

As demonstrated in Table 1, the velocities of up and down saccades with EOG were greater than those with the search coil. The differences between recording methods were significant for up saccades of all sizes at the 0.05 level. The mean peak velocity of 30-deg up saccades with EOG was about 260 deg/sec greater than the mean with the search coil. The differences between down saccades were significant at the 0.05 level for 20- and 30-deg saccades. The mean peak velocity of 30-deg down saccades with EOG was about 120 deg/sec higher than that with the search coil. The velocity differences between up and down saccades with EOG, between up saccades with EOG and the search coil, and between down saccades with the EOG and the search coil were not significantly affected by abduction and adduction.

Infrared Limbus Tracking

In most of the subjects, IR could not accurately record eye movements greater than 10 deg in upgaze or 20 deg in downgaze. At more eccentric gaze positions, the position signal in the polygraph did not increase. As demonstrated in Figure 1 (bottom line), the amplitude of up saccades was underestimated. Mechanical retraction of the upper and lower eyelids did not increase the range of the IR method. The peak velocity of up saccades was also underestimated, as demonstrated in Figure 2 (middle line). Saccades of greater than 20 deg in amplitude were not recorded due to the limited range of the method in the upward field. As shown in Table 1, differences in velocity of up and down saccades of up to 56% were found. Separate calibration factors for up and down saccades and averaged calibration factors for both up and down saccades were used to calculate velocities. However, the velocities of up saccades remained significantly lower than those of down saccades in all fields.

The differences in velocity between up saccades with IR and up saccades with the search coil were significant at the 0.01 level. There were no significant differences between the velocities of down saccades with IR and the search coil.

Discussion

The magnetic search coil method is used much less frequently in clinical eye movement laboratories than are EOG and IR methods. The search coil has the disadvantages of being expensive, causing slight irritation of the eye, and requiring more cooperation of the subject, than do the other methods. However, it was clearly the most accurate technique for recording vertical saccades. Saccades up to 20 deg in the upper field of the orbit and up to 30 deg in the lower field could be recorded without obvious artifacts in their trajectories or errors in calculations of their peak velocities. Up and down saccades to and from the center of the orbit had similar peak velocities for the group of normal subjects. However, a difference of up to 20% was present in individual subjects. Therefore, in clinical tests with the search coil, a difference in velocities between up and down saccades of this degree does not necessarily indicate the presence of an ophthalmoplegia.

EOG is the most commonly used recording technique and has been valuable in studying of the normal physiology and pathophysiology of horizontal eye movements. However, its usefulness in studying vertical saccades was limited. An artifact that was probably caused by eyelid movement produced an erroneously peaked waveform at the end of up saccades and overestimated the peak velocities of up and down saccades. The immobilization of the eyelids did not adequately decrease the effects of the artifact. The difference between the peak velocities of up and down saccades was large in individual subjects, as high as 40%. Ford[7] suggested that an electrical signal from the levator muscle of the lid produced the peaked waveform of up saccades. However, Barry and Melvill-Jones[8] concluded that the initial segment of the eye position recording during up saccades was not affected by lid movement, and that the gradual return toward the baseline was the artifact caused by a change in tissue resistance between the corneoretinal dipole and the electrode. Saccadic velocities were not measured in these studies.

We believe that both types of artifacts are present in EOG recordings. The EOG trajectories of up saccades shown in Figure 1 (middle) of one subject clearly showed that the initial deflections overshot the targets and that the sustained deflections after the saccades were approximately equal in amplitude for up and down movements. The initial overshooting is consistent with Ford's hypothesis. However, EOG trajectories in other subjects did not show overshooting of the targets and did show smaller sustained deflections in the upper field, consistent with Barry's and Melvill-Jones' hypothesis. The latter hypothesis does not predict an error in velocity measurements if the artifact affecting the sustained deflections is compensated for in the calibration factors. We were unable to significantly reduce the differences between EOG and search coil measurements by changing calibration factors. We have recorded EOG signals during attempts to make up saccades in normal subjects whose eyes have been immobilized with forceps and in patients after enucleation. These signals were probably produced by activation of the levator muscle of the upper lid.

The IR limbus tracking method used in our laboratory[14] was inadequate for recording vertical saccades. The range of accurate recording, especially in the upper field of the orbit, was severely limited. The peak velocities of up saccades were underestimated. Other IR limbus tracking methods use circular, rather than rectangular, receptive fields. The photoelectric cells can be rotated in their spectacle frames from their locations over the nasal and temporal limbus used for horizontal recording to locations over the superior and inferior limbus for vertical recording. It is possible that with mechanical retraction of the lids, these IR methods might be more accurate than the one used in our study.

In conclusion, the more commonly used methods of recording eye movements, EOG and IR, were not accurate in measuring the velocity of vertical saccades. EOG was affected by the eyelid artifact, and the range of linearity was severely limited with IR, especially in the upward direction. The search coil method was the most accurate and demonstrated that a significant difference in the group means of velocities between up and down saccades was not present and that eccentric horizontal gaze did not affect velocities of vertical saccades. However, with all three methods, the difference in velocities between up and down saccades in individual subjects could be large. Therefore, peak velocities of vertical saccades should probably be compared with those of saccades in the same direction of the fellow eye in clinical tests for ophthalmoplegia. We have compared the peak velocities between fellow eyes in several normal subjects, and did not find significant differences.

Key words: vertical saccades, saccadic velocity, eye movement, eye movement recording, electro-oculography, infrared scleral reflection, magnetic search coil

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