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Binocular eye tracking with the Tracking Scanning Laser Ophthalmoscope

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ABSTRACT

The development of high magnification retinal imaging has brought with it the ability to track eye motion with a precision of less than an arc minute. Previously these systems have provided only monocular records. Here we describe a modification to the Tracking Scanning Laser Ophthalmoscope (Sheehy et al., 2012) that splits the optical path in a way that slows the left and right retinas to be scanned almost simultaneously by a single system. A mirror placed at a retinal conjugate point redirects half of each horizontal scan line to the fellow eye. The collected video is a split image with left and right retinas appearing side by side in each frame. Analysis of the retinal motion in the recorded video provides an eye movement trace with very high temporal and spatial resolution.

Results are presented from scans of subjects with normal ocular motility that fixated steadily on a green laser dot. The retinas were scanned at 4° eccentricity with a 2° square field. Eye position was extracted offline from recorded videos with an FFT based image analysis program written in Matlab. The noise level of the tracking was estimated to range from 0.25 to 0.5 arc min SD for three subjects. In the binocular recordings, the left eye/right eye difference was 1–2 arc min SD for vertical motion and 10–15 arc min SD for horizontal motion, in agreement with published values from other tracking techniques.

1. Introduction

Recent advances in retinal imaging with the scanning laser ophthalmoscope have led to retina based eye trackers that rival high end systems like the dual Purkinje image tracker and the magnetic induction search coil. Eye motion during retinal scans produce artifacts in the image that distort each recorded frame with shear, compression, stretch, or twist, depending on the eye motions. Removal of these distortions allows averaging of multiple frames for improved signal to noise ratios. This process of removal also yields a record of the eye motion that occurred during the recording (Mulligan, 1997; Stevenson, & Roorda, 2005, Stevenson, Roorda, & Kumar, 2010). This analysis was initially conducted off line with recorded video. More recently a robust real time tracking system has been developed that allows stabilization of targets on chosen retinal locations with precision on the order of an arc minute so that individual cones can be targeted and stimulated repeatedly (Arathorn et al., 2007).

Although adaptive optics (**AO**) provides the best possible images in retinal scanners, scanning through the natural optics of the eye can usually provide images of sufficient quality for tracking. The Tracking Scanning Laser Ophthalmoscope (Sheehy et al., 2012) or TSLO is a non-AO system that scans the retina over a 1–5° field with sufficient contrast and resolution to see individual cones over most of the retina. Real time image analysis associated with the TSLO provides an on line estimate of horizontal and vertical eye position with an accuracy of better than an arc minute, and it produces analog output signals for use outside the TSLO. This system has recently been combined with an OCT scanner to improve the quality of volumetric images (Vienola et al., 2012).

Fixational eye movements recorded with retina scanners have to date been limited to monocular eye movements. Here we describe a modification to the TSLO that allows for recording of both eyes simultaneously with a single scanner. Real time tracking of the two eyes has not yet been implemented, so we report on results from off line analysis of the videos that show eye motion features comparable to the best high precision eye tracking systems. Briefly, we split the optical path with a knife edge mirror so that half the horizontal scan goes to one eye and half to the other, resulting in a split field image containing simultaneous

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records of the two eyes. The noise level is well under an arc minute, and the statistics of binocular fixation match those reported previously with the optical lever and search coil techniques.

For binocular tracking, one could employ two TSLOs to get full field tracking of each eye independently, and obtain real time eye motion for each eye. However, it is also possible to modify a single TSLO to image both eyes simultaneously for binocular tracking. Here we describe a method for dividing the optical path so that half the recorded field is from the right eye and the other half is from the left eye. Analysis of the motion was conducted off line after splitting the video in half. For comparison, a full field video from one eye was split in half and analyzed the same way, to obtain an estimate of the noise level of eye motion extraction. Results show that this system has a noise level of below one arc minute and thus can resolve the microsaccades and drifts of fixation.

2. Methods

The layout of our system is shown in schematic form in Fig. 1. For a complete description of the TSLO design and performance the reader is referred to Sheehy et al. (2012). Briefly, an 840 nm diode source is collimated to form a beam that is deflected horizontally at 15 kHz by a resonant scanner and vertically at 30 Hz by a mirror galvanometer scanner. The scanned beam is relayed by concave mirrors so that the pivot point of the scanners is conjugate to the subject's pupil. The eye's own optics focus the scanned beam to a point on the retina. Reflected light from this point travels back along the same optical path, is descanned by the same deflectors, and is then focused on a pinhole to reject scattered light from outside of the plane of focus. A photomultiplier tube detects the light that passes through the pinhole. The signal from the PMT is recorded by a special purpose video capture card that is synchronized with the scanners. The result is an image of the retina over the area scanned by the point of light (Fig. 2).

For the binocular modification, a knife edge mirror (FM3 in Fig. 1) was placed at a retinal conjugate point between the scanners and the eye. The mirror was positioned so that it deflected half of the horizontal scan into a second path and thereby into the left eye of the subject. The result is a split field view, with the subject's right retina on the left half of the video frame and the left retina on the right half (Fig. 3). The knife edge of the mirror scatters a small fraction of the light, resulting in a black line down middle of the frame.

Subjects were first aligned with the right eye path by fine adjustment of the chin rest/forehead support. The left eye was then aligned with the system by adjustment of the last two mirrors in the optical path. This process was somewhat tedious and we did not attempt to also precisely align the scans to corresponding retinal areas, as this requires adjusting five degrees of freedom (x, y for pupil alignment, and x, y, t for retinal alignment).

Subjects monocularly fixated a 530 nm green laser dot projected on the wall about two meters away, seen by the right eye through a beam splitter. The retina(s) were imaged at about 4° eccentricity (superior field) with a two degree square raster. Subjects had natural pupils and were emmetropes needing no optical correction. Subjects gave informed consent and all procedures were approved by the University of California Berkeley IRB in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

Five subjects (4 Male, 1 Female, age range 28–54, with normal ocular motility and no retinal pathology) in all were tested with this system, but here we report results from three of them. The other two are not reported because we were unable to obtain sufficient quality images from the left eye to recover the eye movement traces. Two of the five had a very small, subclinical (<.5°) upbeating vertical nystagmus (see Fig. 6).

The effect of poor quality images is to reduce the peak value of the cross-correlation between the reference image and the strip of video being analyzed. When this peak gets closer to the background noise, false matches are occasionally higher and the resulting eye trace shows artifactual jumps in position. In order to avoid these artifacts, our algorithm applies a set of tests to the data and rejects video that fails to pass the tests. For the current analysis, blinks and low light level images were rejected when the average

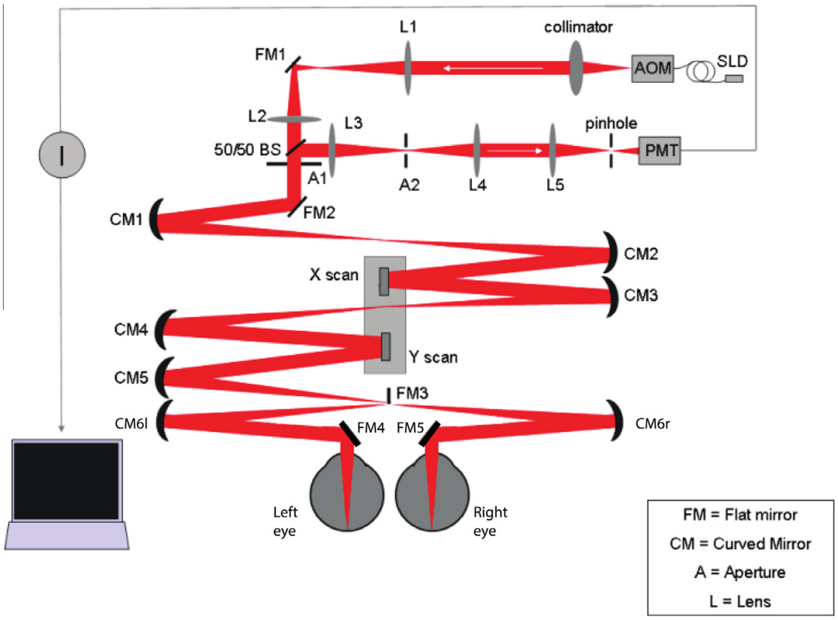

Fig. 1. Schematic layout of the binocular modification to the Tracking Scanning Laser Ophthalmoscope (modified from Sheehy et al., 2012). Mirror FM3 is placed at a retinal conjugate point, splitting the field into left eye and right eye halves. Each half of the scan is reflected by a concave mirror and a flat mirror into the respective eyes. The resulting scan produces a split field image with left and right retinal images side by side in the each frame. The horizontal scanner is a polished bar resonating at 15.4 kHz and images are collected during a 26 µs time window during one direction of scan, so left and right eye samples are collected about 13 µs apart. Eyes are not shown to scale.