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New instrument for monitoring eye fixation and pupil size during the visual field examination

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Abstract—*A new instrument for the monitoring of eye fixation and pupil size during the visual field examination is described. Particular attention has been given to design an instrument adapted to clinical measurements, requiring minimum subject training, co-operation, discomfort and set up time. Relatively free head movements are permitted by the evaluation of eye orientation from the displacement of the corneal reflection with respect to the centre of the pupil. Considerable thought has also been given to the minimising of costs to permit the introduction of the instrument in the ophthalmic clinic.*

Keywords—*Eye fixation, Pupil size, Visual field examination*

1 Introduction

SINCE the introduction of low-cost l.s.i. technologies, sophisticated data-processing techniques are becoming available for many new clinical applications such as the visual field examination. The wide range of benefits to be expected from these techniques has already been described elsewhere (HACHE *et al.* 1976, 1980; CHARLIER and HACHE 1980). One of the major developments is automation which results in a reduction of the operator's involvement and in a better standardisation of examination procedures. There are several prerequisites to the introduction of automation among which the development of sensors and effectors which replace the sensors and effectors of the practician. We have already described the instrument used for the generation of visual stimuli (CHARLIER 1979, 1980). Another major element of the automatic perimeter is the control of the accuracy of fixation and of the pupil size which are two important parameters during testing of the visual field since they determine the position and intensity of the retinal stimulus. Measurements of pupil size and eye orientation are also of great interest as pupil contractions and eye movements can be elicited by changes in the light distribution on the retina, providing another source of information about the visual field. A previous instrument developed within our team for monitoring these parameters (DUBOIS, 1974) was judged impractical for routine clinical examination because of the use of a contact lens.

In this paper, we describe a new eye monitoring instrument which requires very little subject training, co-operation, discomfort and set-up time and is therefore more adapted to clinical applications.

2 Review of existing methods and instruments

Most of the instruments used in the clinic such as the Goldmann and Tubingen perimeters include a telescope that allows for direct observation of the eye through the back of the screen used for the projection of visual stimuli. The practitioner can obtain some indication of fixation steadiness. However, continous monitoring necessitates constant vigilance throughout the examination and is therefore inconvenient and cumbersome.

Another technique requires the patient to monitor his own eye position. A target is placed so as to just fill the blind spot and to be invisible with proper fixation. When fixation deviates, the target becomes visible and serves as warning to the patient.

More recently, automatic devices have been developed which do not involve the operator and the patient intervention. These instruments continuously compare the light reflection from the iris and the cornea to a background level set during proper alignment. Movement or closure of the eye elicit a warning tone and stop the examination procedure until the patient resumes proper position (HART, 1979).

Recent clinical evaluations of these instruments (PORTNEY and KROHN, 1978, KELTNER *et al.*, 1979) have shown a major inconvenient in their sensitivity to head motion which results in the need for frequent reinstruction of the patient and readjustment of the eye

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monitor. These instruments are tracking the position of the iris or the corneal reflection and they do not separate lateral and rotary motions of the eye.

An eye rotation of 1° can be shown to be equivalent to a head transverse motion of only 0·17 mm (Ditchburn and Ginsborg, 1953). Maintenance of the head fixed within such limits is difficult, uncomfortable and not suitable for a clinical examination lasting for more than 15 minutes.

3 Method selection

A desirable method for controlling eye fixation would allow relatively free natural head movements. It should measure the rotation of the eye independently of its position. Other major considerations in the design of a clinical instrument are that minimal subject training, co-operation, discomfort and set-up time should be required. Furthermore, the eye-monitoring device should be positioned in such a way that it does not interfere with the visual field examination.

Several methods have recently been proposed which provide an answer to these different constraints:

The eye orientation can be determined by measuring features of the eye that only change with rotation. For instance, the shape of the pupil, or more precisely its ellipticity, seen by a fixed observer, varies as the eye rotates (Young and Sheena, 1975). Unfortunately, this method requires complex geometrical calculations which make its implementation quite difficult.

Another solution is to measure the relative positions of some details of the eye that move differently as the eye rotates. Their difference is not affected by translation movements and is only related to rotations. Cornsweet and Crane (1973) used the first and fourth Purkinje images which are reflections that occur at the front of the cornea and at the back of the lens, respectively. However, the fourth Purkinje image is quite difficult to detect at the distance from which the monitoring device is operating, i.e. 50 cm away from the eye. As the reflection coefficient of the lens is very small (around 2×10^{-4} according to Legrand, 1964), this method would necessitate high illumination levels which could be dangerous to the retina. Another solution is to measure the position of the corneal reflection relative to the pupil (Merchant and Morrissette, 1974). Several instruments have been developed using this solution (Young and Sheena, 1975). There are presently at least two systems commercially available: the Honeywell Oculometer and the Whittaker Corporation eye movement monitor. These systems are expensive (around $40,000) which may be unacceptable for a component of a clinical instrument.

However, we managed to reduce considerably the cost of hardware with the development of a video image processing system combining wired logic to a microprocessor. We will describe the technological features of this instrument, the different problems resulting from its adaptation to visual field measurements in a clinical environment, the performances which are obtained and the results of a preliminary clinical evaluation.

4 Implementation

4.1 *Optical design*

A proper choice of the position and the bandwidth of light radiation prevents the interference of the eye-monitoring device with the visual field examination. The eye of the patient is viewed through an aperture of the projection screen in correspondence with the blind spot (Fig. 1). It is illuminated with near i.r. radiation obtained from a tungsten filament lamp filtered to the 800–900 nm band, which is sufficiently far into the i.r. region to be almost invisible. The boundary between the pupil and the iris, which normally exhibits very low contrast, is enhanced with the bright pupil effect: the illumination and collection apertures of the optical systems are made coincident so that incident light rays are refracted back from the retina and back light the pupil (Fig. 2). The resulting image of the eye shows the

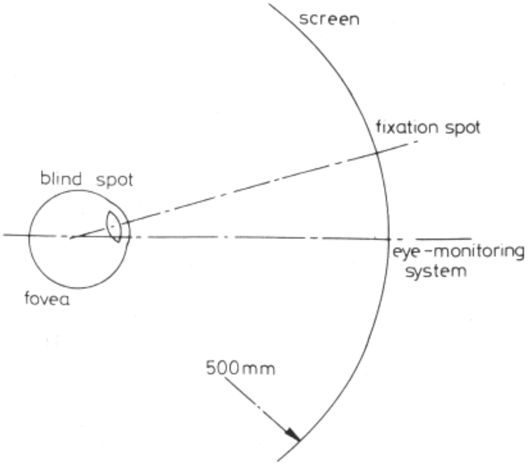

Fig. 1 *Position of the eye-monitoring system*

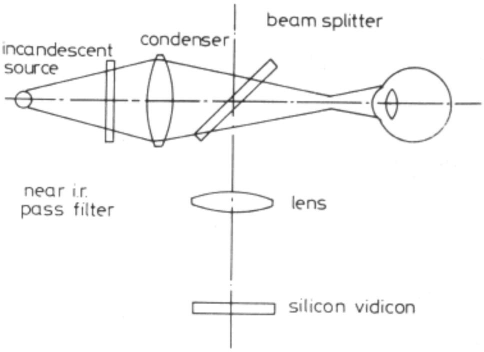

Fig. 2 *Schematic of the optical system*

pupil as a bright disk against a dark background (Fig. 3).

4.2 *Image sensor*

A standard 625 interlaced scanning lines, 50 frames per second, television camera is used as an image transducer. The conventional vidicon is replaced by a vidicon employing a silicon diode array target, which presents a much higher sensitivity in the near infra-red spectrum. The resolution of 312 lines per frame allows for a precision of one degree of eye angular motion with an approximate 2 cm by 2 cm image area at the eye.

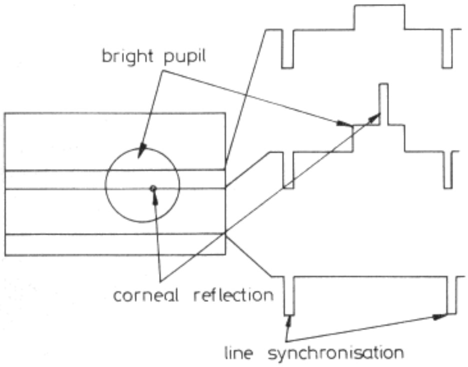

Fig. 3 *Video image and signals*

4.3 *Image processing*

Eye direction and pupil size information are extracted from the camera video signal. Typical lines of this video signal are presented in Fig. 4. Eye direction is evaluated from the relative positions of the corneal reflection (X_C, Y_C) and pupil centre (X_P, Y_P).

The pupil centre is determined as the barycentre of the pupil perimeter,

$$X_P = \frac{1}{2n}\left(\sum_i X_{i1} + \sum_i X_{i2}\right) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$Y_p = \frac{\sum i}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where X_{i1} and X_{i2} are the co-ordinates of the beginning and end of the pupil on scanning line number i and n is the total number of lines.

The differential position between the pupil centre (X_P, Y_P) and the corneal reflection (X_C, Y_C) can be obtained as:

$$X_D = X_P - X_C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$Y_D = Y_P - Y_C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Furthermore, the pupil surface area S can easily be determined from the same set of data:

$$S = \sum_i X_{i2} - \sum_i X_{i1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

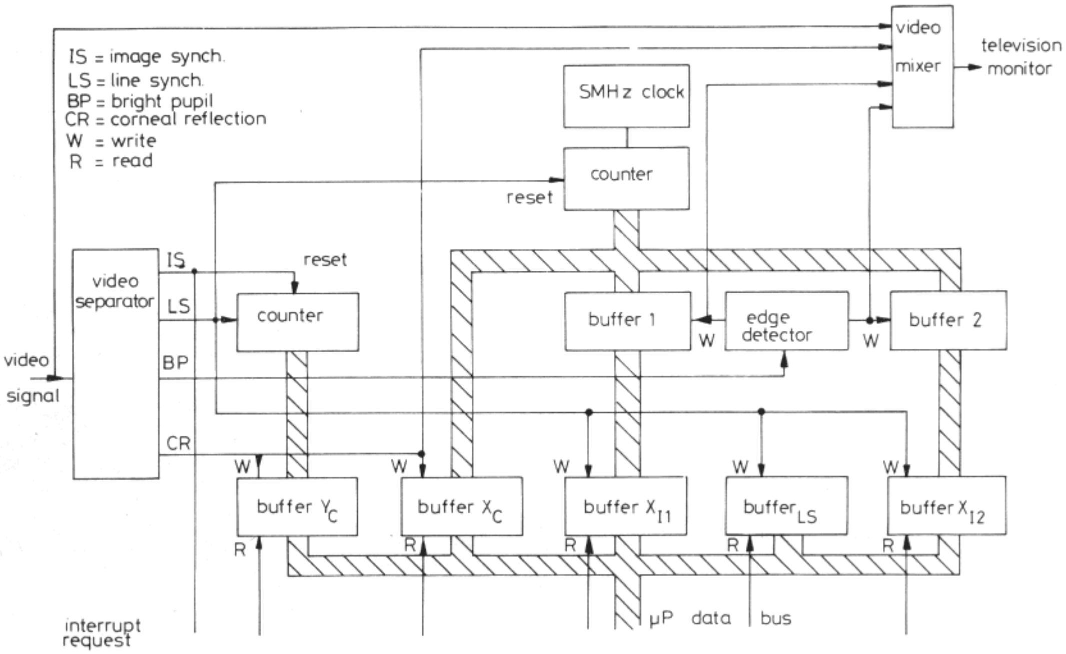

Fig. 4 *Video preprocessing interface*

The design of the firmware implementing these calculations was guided by the need for keeping costs to a minimum. On account of the large bandwidth of the video signal from the infra-red camera (5 MHz), data sampling and processing requires very fast logic components. A fast bipolar bit slice processor using e.c.l. or t.t.l. technology would provide a cycle time as low as 50 ns. However, it requires expensive development costs and necessitates specific experience which is not presently available in our laboratory. On the other hand, signal processing using a specially made set of electronic circuitry does not offer the development and processing capabilities of microcomputers.

A compromise is reached with the association of a preprocessing t.t.l. interface with a low cost microprocessor using m.o.s. technology and providing a cycle time of 500 ns. The logic interface determines the co-ordinates of the beginning (X_{i1}) and end (X_{i2}) of the bright pupil over each scanning line. Further calculations are carried out by a Motorola 6802 microprocessor.

The block diagram of the interface is shown in Fig. 4. The video signal from the infra-red camera is analysed to separate its various components: frame and line synchronisation pulses, bright pupil and corneal reflection. The signal from a 5 MHz clock is fed into a counter which is reset by the line synchronisation pulse and allows for the determination of positions over each scanning line. The content of this counter is transfered to buffers at the leading and trailing edges of the bright pupil and corneal reflection. A double buffering system is used for the pupillary measurements to eliminate the possibility of data change before the reading operation by the microprocessor takes place. Such a system is not necessary for the corneal reflection measurement as the reading of corneal data is made only at the end of each image. The corneal reflection vertical position (Y_c) is determined by counting the line synchronisation pulses from the beginning of each image. The detection threshold of the corneal reflection and bright pupil are adjusted manually. The detected bright pupil contour and corneal reflection are mixed with the video signal of the camera and displayed on an infra-red television monitor. The resulting image provides a feedback to the user about the data acquired by the processing system and allows the adjustment of the detection thresholds.

A block diagram of the microprocessing system is shown in Fig. 5. A 6802 Motorola system is used which includes 128 words of random access memory. A programmable memory chip provides storage space for the program. Two buffers are used for the communication of data between the microprocessor and a supervising terminal or processor.

The flow chart of the microprocessor program is outlined in Fig. 6. Its execution is synchronised with the television raster scan by the frame synchronisation pulse which triggers an interrupt request. One image out of two is used for the acquisition of X_{i1}, X_{i2}, X_C and Y_C and for the simultaneous calculation of $\sum X_{i1}$ and $\sum X_{i2}$. Several algorithms have been introduced in order to reduce measurement artefacts. The X_{i1} and X_{i2} co-ordinates are not taken into account if the

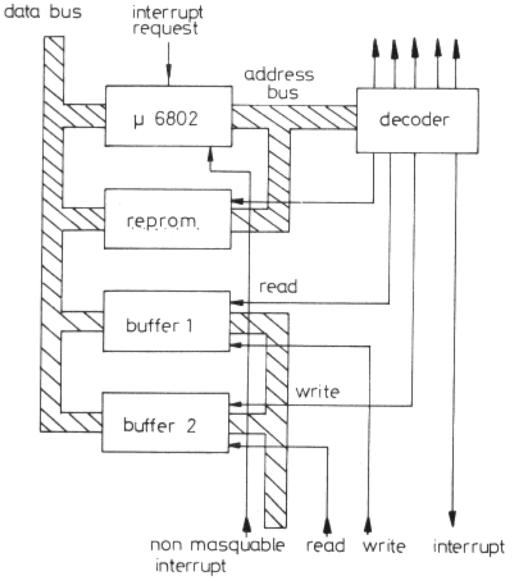

Fig. 5 *Microprocessing system*

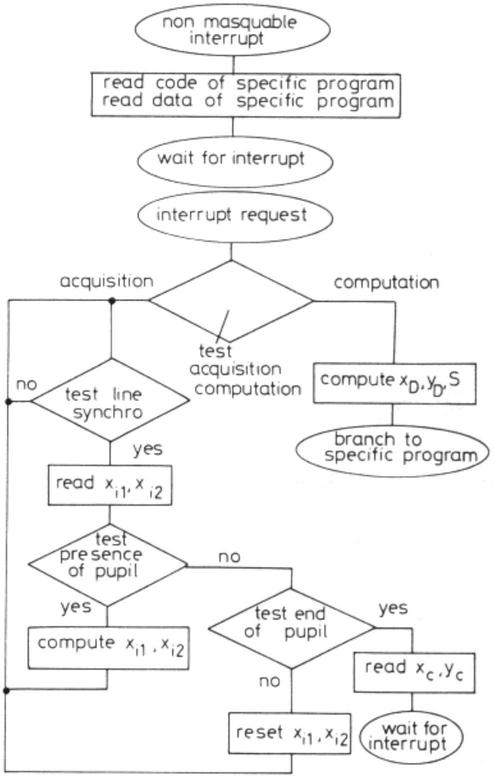

Fig. 6 *Flow chart of program*

width of the pupil line or the number of consecutive lines which belong to the pupil fall short of specified values, allowing the elimination of background noise. The corneal reflection is only validated within a control window centred on the pupil, which prevents the detection of parasite reflection taking place on the eyelids corners or on corrective spectacles.

During the consecutive frame, the eye orientation and pupil surface area are calculated using eqns. 1 to 4. Thereafter, several specific programs can be implemented, corresponding to different monitoring functions required for the automatic visual field examinations.

4.4 *Specific software implementations*

The selection of the different available programs is made with a code number stored in the communication buffer. This code number is read by the microprocessor upon reception of a nonmasquable interrupt.

A first program transfers the eye direction and pupil surface area to the output communication buffer. These data are available to the supervising processor for the analysis and detection of pupillary and oculomotor reactions to the projection of visual stimuli.

A second program is used for the initiation of fixation control. The values (X_D, Y_D) are averaged over a series of 32 consecutive frames. The result (X_R, Y_R) is validated and used as a reference if the standard deviation of the (X_D, Y_D) distribution falls short of a specified value, indicating that no eye movement occured during the initiation. These results are transmitted to the supervising processor via the communication buffer.

A third program provides a control of fixation. The measured values (X_D, Y_D) are compared to a control interval centred on the reference (X_R, Y_R) which was determined previously by program number 2. An error signal is elicited that triggers an interrupt of the supervising processor every time the eye fixation deviates from the control interval for more than 20 consecutive images. This 400 ms time delay allows for the elimination of eye blink artefacts.

Other programs are available for measuring the eye orientation and testing fixation from the corneal reflection alone. These measurements which, as mentioned previously, are very sensitive to head movements are used when the bright pupil effect is not sufficient for allowing the detection of the pupil contour.

4.5 *Interaction of the eye monitor with examination procedures*

The interaction of the eye monitor with the supervising processor, which is in charge of the examination procedures, will briefly be described. The initiation of fixation control (program number 2) is usually performed at the beginning of the examination session. If the initiation is successful, i.e., if no movements occur during the measurements, the control of fixation (program number 3) is automatically validated. Otherwise, the initiation can be started again or the examination can be pursued without fixation control, depending on the operator's choice. The examination procedure consists of a series of measurements of the threshold of visual perception. Upon reception of an error signal from the eye monitor, indicating a change in eye fixation, the examination procedure is interrupted and a specific procedure engaged. The interrupted measurement is invalidated, the fixation light is put on a flickering mode and a warning signal is produced. Upon recovery of proper fixation, the interrupted measurement is started again and the examination procedure resumed. Several parameters of the fixation control can be modified by the examination procedure or by the operator during the examination. For instance, a larger control interval can be programmed within the examination procedure for the evaluation of the peripheral visual field which does not require as much precision as the foveolar region. In a same manner, the operator can adjust the control interval depending on the fixation behaviour of the patient.

5 Performance evaluation

Fig. 7 shows eye orientations measured for a matrix of test points located 10° apart and for different head positions within the 2 cm × 2 cm eye monitoring space. Error in measurement of the eye orientation is typically less than ±1°. The described instrument has been tested in the clinic on more than 100 subjects including normal and pathological cases. The control of fixation is found to operate properly on about 70% of the subjects with a 5° control interval. The instrument was found to be very convenient for routine

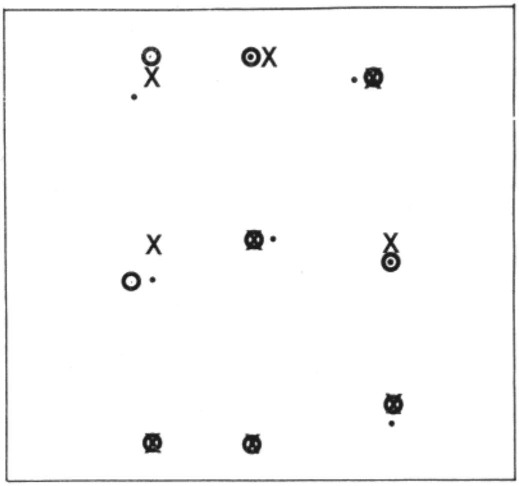

Fig. 7 *Eye orientations measured for a matrix of test points located 10° apart and for different head positions*

clinical examinations as it does not require any subject training, co-operation and discomfort. Head movements within 10 mm amplitude do not affect the results. The examination can be interrupted at any time and still no initiation of the eye monitor be needed when the examination is resumed.

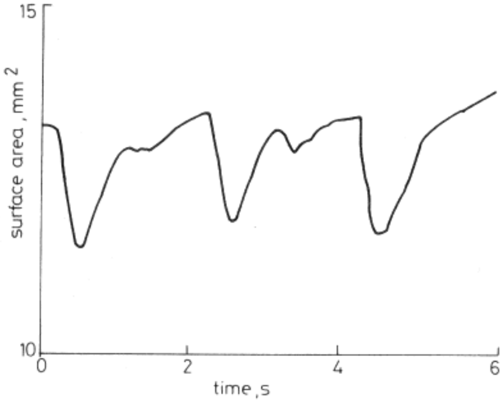

Fig. 8 *Pupil surface area responses to visual stimulation*

Fig. 8 shows the pupil surface area recorded on a subject submitted to a series of flash stimulations. Flash occurences are indicated by vertical lines and are followed by contractions of the pupil. Pupil surface area is measured with an accuracy better than 2% and a sampling frequency of 25 Hz.

Several problems have been encountered during the clinical evaluation. The pupil can hardly be detected using the bright pupil effect when it is less than 2 mm in diameter or when the ocular mediums are opaque. These situations are found in patients with glaucoma administered with pilocarpine or in patients with cataracts. Bad results are also obtained when the eyelids or eyelashes obstruct a part of the pupil. New processing algorithms are presently under development to take these artefacts into account.

6 Conclusion

A new instrument for the monitoring of eye fixation and pupil size during visual field examinations has been presented. Eye movements are measured by tracking the corneal reflection with respect to the centre of the pupil. This method allows free head movements within 10 mm intervals and is therefore well adapted to clinical examinations. The eye orientation is measured with an accuracy better than ±1° and a sampling frequency of 25 Hz. The eye monitor includes a standard television camera with a silicon vidicon, a preprocessing video interface and a microprocessor. This design results in a rather inexpensive instrument which provides an answer to one of the main problems of automated visual field examinations.

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