1 Introduction

Congenital nystagmus (CN) is a disorder of ocular motility which is characterised by a more or less regular rhythmic sequence of conjugate eye movements alternately in both directions of gaze. The techniques currently available for recording eye movements are the infra-red (IR) reflection technique (Young, 1963), DC coupled electroneystagmography (Weber and Daroff, 1971), retinal cinematography (Dell’Osso et al., 1974) and the magnetic field technique (Robinson, 1963). These allow accurate and quantitative measurements of eye position in order to study the oculomotor disorder of CN. However, there are few reported studies on the quantitative assessment of eye position recordings in CN, despite the consolidated clinical knowledge which exists about CN operative techniques, their qualitative effects and the surgical strategies to treat the associated anomalies (e.g. amblyopia, strabismus).

A pioneering work in this direction was accomplished by Dell’Osso and co-workers (Dell’Osso, 1973; Dell’Osso et al., 1972). They used nystagmus intensity (Dell’Osso et al., 1974)—defined as the product of average peak-to-peak amplitude and average frequency of the eye oscillations—for measuring the severity of nystagmus and the effect of surgery. They showed that, in a patient with CN which appeared from the nystagmus intensity plot as having a lateral neutral zone of minimum nystagmus (null zone), the null angle (i.e. the gaze angle of the null zone) is shifted to the primary position of gaze and the null zone broadens after classical CN surgery (Dell’Osso and Flynn, 1979).

Unfortunately these findings are based on very poor proposed statistics (three cases, although selected) and need further investigation. However, a large increase in statistics is unrealistic, due to the small number of CN operations each year (for example there are about ten cases per year in the Oculistic Department of our University).

In addition, the quantitative approach to the evaluation of CN surgery can be made more accurate by using standard methods of spectral analysis, which have also proved useful in testing theoretical models for explaining CN (Reccia et al., 1986).

In this work we re-analyse critically the method of Dell’Osso and co-workers of using the nystagmus intensity plot pre- and postoperatively (nystagmus intensity against gaze angle) for the evaluation of surgery. Although a measure of amplitude and frequency of the eye position waveforms according to spectral analysis—extended to the study of patients treated with Kestenbaum’s or Anderson’s or Cüppers’ surgical technique—should allow us to draw more definite conclusions, in fact due regard to the confidence limits of the measurements brings us to be rather cautious both from the methodological and from the clinical point of view.

2 Materials and methods

Eight patients with CN were examined. The subjects were seated in a lighted room and asked to stare at a light spot successively placed at seven different angular positions (from -30° left to +30° right with 10° steps) with respect to the primary position. The distance from the target was 0.33 m.

The eye movements were recorded by electroneystagmography (ENG) (accuracy of about 0.5° with a Beckman AC-coupled EEG instrument. A skin electrode was placed on the outer canthus of each eye and an earth electrode on the forehead. A low-pass analogue filter (-3 dB at 15 Hz) avoided the recording of muscle activity. After elimination of the artefacts due to blinking of the eyelids by visual inspection of the recorded waveforms, data were digitised at 270 Hz. Owing to the AC coupled recording, high-pass filtering of the input signal was produced, with a cutoff frequency of about 5 Hz, thus setting a low frequency limit to our study. Moreover, since we found that the eye position signal dropped by more than 30 dB from 5 to 25 Hz, to avoid undesired high-frequency components we used a low-pass digital filter (64 points, finite impulse response filter, Remez exchange algorithm) with an upper band-edge of 25 Hz (-3 dB) and studied the frequency behaviour of the eye position signal within this band. We then computed the smoothed power spectrum estimate of the eye position signal, using the method of the lag window and the Parzen window (Jenkins and Watts, 1968). The width of the lag window was always chosen to be T/2, where T is the duration of recording of the ENG signal considered, so that the confidence limits for the esti-
mated spectrum at each frequency were fixed independently of $T$. On a logarithmic scale these confidence limits are constant at all frequencies; hence the power spectra were also computed in decibels. We note that the correction on the power spectrum due to the instrumental high-pass filtering was 3 dB at 5 Hz and decreased quadratically to 0.2 dB at 25 Hz.

We regarded each signal recording as a realisation of a stochastic process, supposed stationary at least to the second moment. In fact, different samples of signal recorded at different times, for the same patient and angular position, resemble each other only in their average properties, owing to the presence of noise and small random changes in the nystagmus waveform pattern.

A typical power spectrum of our nystagmus waveforms is shown in Fig. 1, where signal power in logarithmic units is plotted against frequency in Hz. The presence of a well defined peak in this plot indicates the occurrence in the signal of an oscillation with average frequency corresponding to the abscissa of the peak, the average amplitude of this oscillation being related to the ordinate of the peak. The error in the frequency and in the power of the peak is determined by the spectral resolution (in our case, the bandwidth of the lag window) and the width of the 95 per cent confidence interval of our spectra, respectively. Since we found that the greatest power is concentrated in the first peak, sharply emerging above the error, we assumed that its abscissa $f$ and ordinate $P$ suitably measure the frequency and amplitude of the recorded nystagmus waveform.

### 3 Results and discussion

Most patients with CN show a null region, i.e. a range of contiguous directions of gaze in the horizontal plane for which eye oscillations are absent or greatly reduced in amplitude. For these patients, the aims of CN surgery are the following:

(a) to shift the null region, if lateral, to the primary position of gaze
(b) to broaden the null region to a wider range of gaze angles
(c) to decrease the amplitude and frequency of the eye oscillations out of the null region.

These goals might be achieved by different proposed surgical treatments, essentially based on the change of the horizontal extra-ocular muscles (recti) insertion (Ciappers' threads operation) or on the resection and displacement of them (Anderson and Kestenbaum), the Ciappers' technique being generally applied when the null region is absent or in the primary position of gaze.

To evaluate the nystagmus severity variations induced by the surgery, Dell'OssO and co-workers plotted the product of the average peak-to-peak amplitude and the average frequency of the eye position waveforms against the gaze angle, before and after surgery: they called this product 'nystagmus intensity'. This combination of variables not only satisfies the need for a more compact description of the phenomenon, but also implies that amplitude and frequency compensate each other in a multiplicative way. Of course, if they both decrease (or increase), the improvement (or the worsening) of the nystagmus is evident. But if they change in opposite directions, it is certainly a gross simplification to assume that the increase of, say, frequency is balanced by a proportional decrease of amplitude. Such a choice can be accepted only for lack of a better alternative, as the simpler one. From the inspection of the nystagmus intensity plots, Dell'Oso and co-workers were able to document the beneficial effect of the surgical treatment. However, no error analysis was given regarding the measurement of frequency and amplitude.

In this communication the spectral analysis method supplies an estimate of the peak frequency $f$ and the peak power $P$ of the main spectral component of the eye position recording, so that here the nystagmus intensity can be defined as the product $Pf$. In this approach the uncertainties on $P$ and $f$ are represented by the 95 per cent confidence interval $\delta P$ and the lag bandwidth $\delta f$, respectively. From trial tests using the window-closing procedure (Jenkins and Watts, 1968) it was found that a good resolution of the spectral peaks, with an acceptable bias of the power spectrum estimator, was obtained with a lag window width of half the time duration of the sample. Hence, taking into account the general rule that the product of variance of the spectral estimator times lag bandwidth is a constant, $\delta f$ was also determined.

This analysis led to values of $\delta f$ comparable with the range of variations of $f$ over the gaze angle, whereas $\delta P$ values are generally smaller than the variations of power with the gaze angle; hence only power behaviour can be significantly deduced from our data. The same happens for the variations of $P$ and $f$ pre- and postoperatively, where the frequency is slightly altered and the power can be significantly modified.

Now, if we plot $I = Pf$ against the gaze angle (Fig. 2), the error $\delta I = P\delta f + f\delta P$ will depend not only on $\delta f$ and $\delta P$ but also on the absolute values of $P$ and $f$ at each gaze angle, and of course the relative error on $I$ will be the sum of the relative errors $\delta P/P$ and $\delta f/f$. From our data, we then derived a relative error $\delta I/I$ of the order of 100 per cent, so that only dramatic changes (either over gaze angle or after surgery) in the nystagmus intensity $I$ can be appreciated. On the contrary, the $P$ plot more easily allows the assessment of the effect of surgery on the nystagmus amplitude, $\delta P/P$ being of the order of 40 per cent (Fig. 3).

On the other hand, it is to be noted that the nystagmus intensity $I$ equal to amplitude times frequency of the eye movements essentially depends on the maximum velocity of the eyes; hence, owing to the experimentally established functional dependence between maximum (saccadic) velocity and eye motion amplitude (Zuber and Stark, 1965), nystagmus intensity variations are likely to be caused by...