Technical note

Precision LED-based stimulator for focal electroretinography

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Abstract—*The authors discuss the technical problems commonly encountered in the design of devices used in the functional analysis of the central retina (macula) and its neuronal elements. They present a simple effective solution for introducing some of the most recent and interesting results of neurophysiological and psychophysical research into the eye clinic.*

Keywords—*Electroretinography, LED, Stimulation, Macula*

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1 Introduction

RECENT STUDIES indicate that a functional analysis of the central retina (macula) and its neuronal elements is possible by means of focal evoked electroretinographic signals (BURNS *et al.*, 1992). These signals are obtained in response to a small, sinusoidally modulated test light (ABRAHAMS *et al.*, 1995) superimposed on an equiluminant background (BIERSDORF, 1989). The signal emerging from the retinal layers is acquired by eyelid electrodes and is amplified and averaged to improve the signal-to-noise ratio. The resulting waveform is no longer sinusoidal as the stimular was, which indicates the presence of both linear and non-linear components in the system under test (BAKER and HESS, 1984). The dominating harmonics are the first and the second, with a relative ratio strongly dependent on the stimulation frequency (PORCIATTI *et al.*, 1989).

To succeed in the practical realisation of such experiments, which are based on an accurate determination of the frequency response function, it is mandatory to rely on a high-quality sinusoidal stimulation. In certain cases, clinical tests based on psychophysical protocols may also be useful as a control or alternative methodology. This last point involves the necessity of an extremely fine control of contrast, to obtain reliable thresholds detection. In this paper, we discuss the technical problems commonly encountered in the design of these devices and describe how it is possible to solve many of them using ultra-bright LEDs and modern micro-electronics.

2 System design

A flicker stimulator to be used in both electrophysiology and psychophysiology fields should, in particular, feature

- a sinusoidal, undistorted waveform
- a wide frequency range (1–100 Hz), with high resolution (0.1 Hz)
- a fine, steady control of contrast in log steps
- an accurately timed trigger output
- a very low level of electromagnetic interference (EMI).

When temporal modulation is the main issue, LEDs have significant advantages over other types of light source, e.g. CRT monitors, and have in fact been widely used, starting from single devices up to large arrays. Using a given type of LED, the chromaticity of the stimulus is fixed. This is not a severe limitation, because the temporal frequency response function has not been shown to change substantially when stimuli of different dominant wavelength (i.e. 565 and 660 nm) are employed (BURNS *et al.*, 1992). Fig. 1 shows the block diagram of the system; Fig. 2 is a picture of the prototype we realised. The digital frequency synthesiser producing the sine waveform and the LED driver are included in the box. The cylinder is the optical part of the stimulator and contains only the LED array and a dispersion screen.

2.1 *Stimulator and driver*

The stimulator has been built around a metal cylinder, 27 cm in length and 10 cm in diameter, with a polished internal surface. One end is closed by a dispersing plate; the other is closed by a printed circuit board carrying the ultrabright LEDs (peak wavelength 660 nm, luminous intensity 3000 mcd, viewing angle 20 deg.). This arrangement simply makes use of the lens effect of the LEDs to focus the light on the front screen, with no extra optics needed. The use of wide-beam LEDs in a clear plastic scattering box was also considered. In this way it is possible to achieve similar results in a substantially smaller volume. The screen is viewed through a hole in the centre of a Ganzfeld bowl, used to control the surrounding light adaptation. In the final arrangement, the vision field was of 8 deg at a viewing distance of 57 cm.

To modulate the emission of this light source with the necessary linearity, the LEDs must be driven in an appropriate way. Some authors simply used a laboratory waveform generator. Others (SEIPLE *et al.*, 1986) improved linearity by adding a series resistor or, even better, a voltage-to-current converter. As a general rule, if the mean luminance is kept

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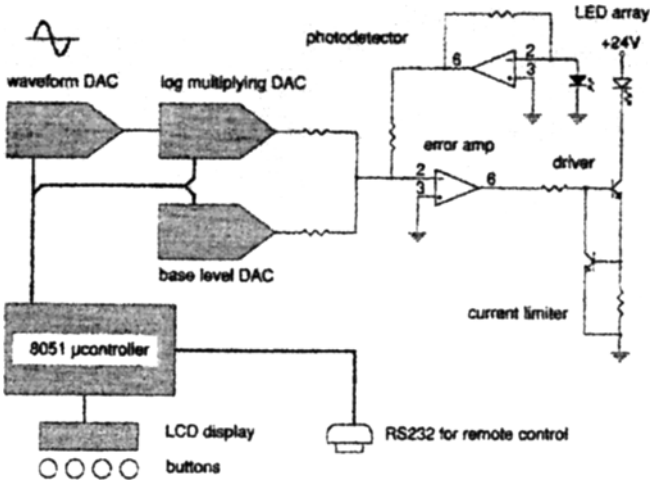

Fig. 1 *Simplified block diagram of LED stimulator. The waveform synthesiser is on the left; the driver stage is on the right*

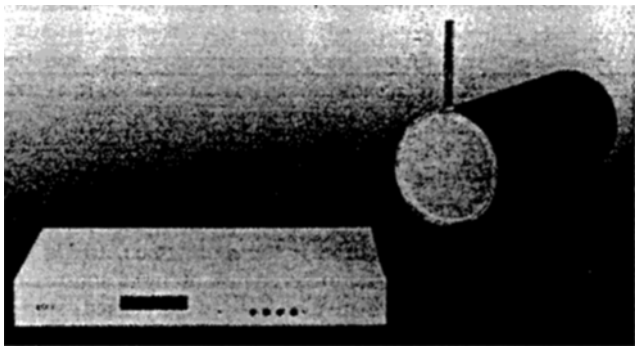

Fig. 2 *Prototype of LED stimulator (shown without the Ganzfeld)*

high and the maximum contrast is reduced, the resulting linearity increases and, in some cases, may be acceptable, even when such simple drivers are used. An interesting approach (BURNS *et al.*, 1992) is that of digital (on/off) modulation that, in principle, has an intrinsic perfect linearity. The desired modulation is obtained as a variation of the on:off ratio (duty-cycle). This solution is satisfactory for electrophysiological experiments but usually lacks in dynamic range. Another practical limitation of all these drivers arises when low stimulation frequencies are needed. The output of an LED is highly sensitive to temperature variations at the junction, caused not only by fluctuations in room temperature, but by internal power dissipation too. At low frequencies, a temperature ripple appears, and a luminance reduction up to 10% of peak value can ensue, with amplitude and phase variable according to signal amplitude and frequency. Such a phenomenon is not easy to compensate in a direct way and may alter the symmetry of the sinusoidal waveform when high contrast and low frequency are simultaneously required.

To overcome these problems we adopted a closed-loop driver (Fig. 1). There are eight LEDs connected in series: seven are real light sources, and one, located in a blind cavity, generates a feedback signal by means of a temperature-stabilised photodetector. Assuming that the output of the photodetector is linear, and that the light emitted by the LED in the cavity is proportional to the LED array in the cylinder, it is possible to obtain by feedback the desired linearisation of the transfer function of the stimulator. At this point, a small error source may yet appear, as a result of slight variations in the spectrum of the emitted light at different luminance levels. To obtain a correct feedback signal, it is therefore important to use a photodetector with a spectral response approximating the standard visibility function.

The driver thus realised proved to have a maximum continuous output of 200 cdm^{-2}, with a 100% intrinsic contrast. To assess the waveform quality, we focused a photometer* on the stimulating surface to obtain a voltage signal proportional to luminance. The harmonic distortion figures were then obtained using a dynamic signal analyser†. The spectrum showed significant rows only in correspondence of the second and third harmonics. The total harmonic distortion (THD) turned out to be less than 0.3%, with an almost constant value over all the specified frequency range. Contrast and luminance were left unchanged at their maximum values during the test.

2.2 *Synthesiser*

The synthesiser is based on a microcontroller‡ interfaced with three digital-to-analogue converters (DACs) and used to generate the sinusoidal waveform, control its amplitude (multiplying DAC) and output a voltage level to establish a mean luminance (Fig. 1).

The 12-bit DAC for sinusoid generation is used at full voltage swing in bipolar mode. In this way, resolution is optimised and the 0-phase point may be simply detected by a zero-cross comparator with AC hysteresis. The result is a reliable trigger signal, as is required for the study of phase response in the upper range of frequencies.

The generation of numerical values for the sampled waveform is based on an N-module circular scan of a look up table of 12-bit integers, using the technique of fixed sampling frequency and variable step. If F_s is the sampling frequency, and S is the step, the resulting output frequency is $F = S^*F_s/N$. The value for F_s is to be much higher than twice the maximum frequency, as stated by the Nyquist criterion, to avoid aliasing and simplify the interpolation filter. On the other hand, given a certain value for N, too high a value for Fs will worsen the frequency resolution F_s/N. If we wish to have both good resolution and high sampling frequency, we have to adopt very high values for N, which means 2^*N bytes of memory occupation for the look-up table. In our case, we have $F_s = 6451.6$ Hz (1 MHz/155) and $N = 64512$ (252*256). The result was a 0.1 Hz resolution, with an oversampling factor of 32. The apparently impractical value of N (corresponding to a table of about 128 Kbytes) was made possible by the use of a real-time, linear interpolation algorithm between the values of a much smaller table (252 points). The worst-case interpolation error was computed and found to be much smaller than the quantization error associated with a 12-bit DAC.

The use of a separate multiplying DAC for amplitude control greatly alleviates the computational burden on the microcontroller, without the cost of a digital multiplier. Using a logarithmic device**, we also satisfied the requirement of having a precise attenuation of the stimulus in steps of decibels or fractions, ranging from 0 to −88.5 dB in 0.375 dB steps, corresponding to a 17-bit linear resolution. The user can vary the stimulation parameters from simple front panel console or from a remote controller, using an RS232 interface. The local console consists of an LCD display (2 rows by 16

*Spectra Pritchard 1980, Photo Research, CA, USA

†Hewlett Packard 35660A

‡Intel 8051

**Analog Devices AD7111

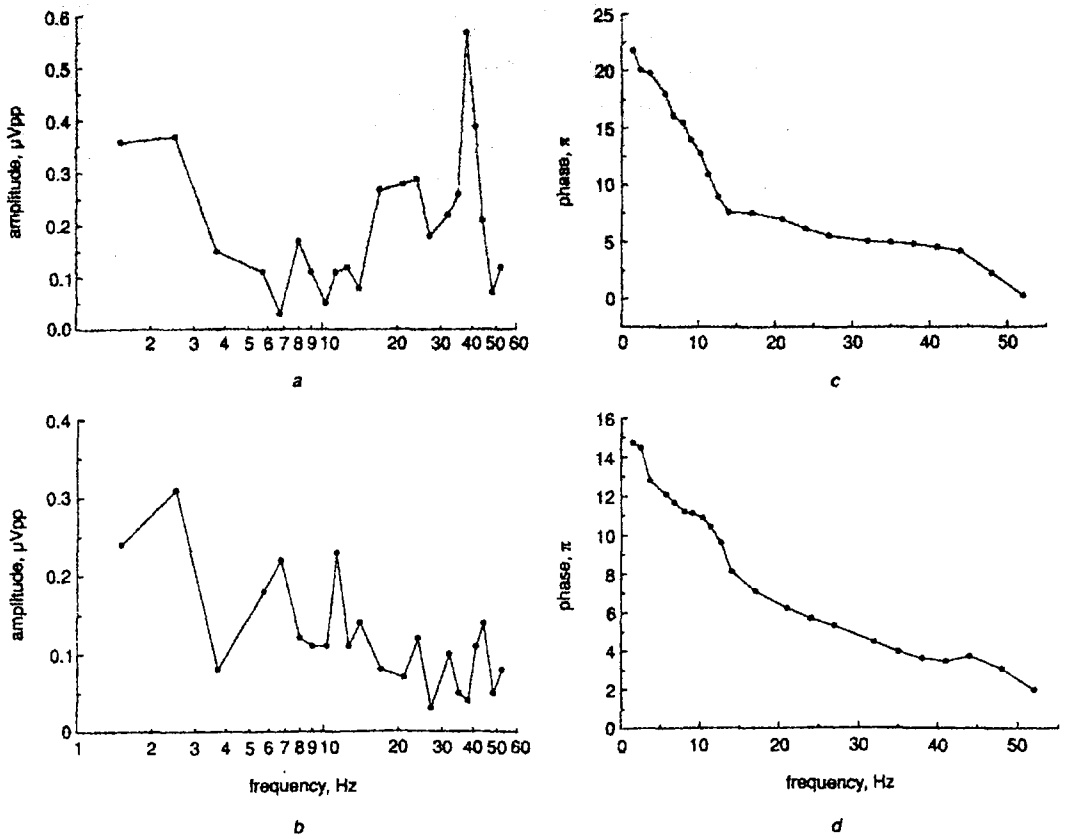

Fig. 3 *Amplitude and phase of the first and second harmonic components of ERG responses, obtained in a normal subject. A set of 22 sinusoidal stimuli ranging from 1.5 to 52 Hz was used. The abscissa is the frequency of stimulus*
(a) Amplitude of first harmonic component
(b) Amplitude of second harmonic component
(c) Phase of first harmonic component
(d) Phase of second harmonic component

characters) and four keys that allow parameter selection to be updated, increment or decrement with autorepeat, and start/stop operations. In this way, the system is capable of stand-alone operation, but, in practice, the preferred solution is that of giving the control of the stimulator to the PC performing the signal acquisition. In this way, it is possible to simplify or even automate the management of complex experimental protocols.

3 Results

The stimulator hereby described was used for research and clinical tests in patients affected by various retinal macular pathologies, such as age-related macular degeneration or cone dystrophy. The presentation of general results related to such studies is beyond the scope of this paper, and only a sample of normative data is presented in Fig. 3, to show the performance level of the method. A normal adult male was subjected to 22 different focal stimuli, with uniform contrast and mean luminance (92% at 80 cdm^{-2}) and frequencies ranging from 1.5 to 52 Hz. Stimuli below 10 Hz or above 40 Hz, scarcely reported in literature, show an interesting behaviour, particularly if we compare the different shape of the first and second harmonic traces. The first harmonic amplitude, mainly related to photoreceptor activity, shows an initial low-pass behaviour followed by a peak at about 40 Hz and a subsequent marked decay. Experiments with younger subjects (data not shown) yielded measurable responses up to 70 Hz. The second harmonic trace shows a more complex shape, with several peaks that may be interpreted as the result of the interaction of cell populations in the inner retina having different temporal responsiveness. The close spacing of test frequencies is useful to study this phenomenon and eliminate phase uncertainty at higher frequencies. The 0.1 Hz resolution also proved useful to avoid undesired time correlation between the stimulus and sources of periodical noise, such as power lines or computer monitors.

4 Conclusions

The use of LED-based stimulators is a long-established technique in electroretinography. Nevertheless, it seems that no particular effort has been recently made to develop precision LED stimulators that could give this method a more specific advantage over CRT monitors or other light sources. In our work, we were faced with two problems: the generation of the stimulating waveform, and the driving of the LED array. The first issue can be solved using the technique of digital synthesis, whereas the second still poses difficulties that may require further study.

As some results suggest (FALSINI *et al.*, 1994), the study of ERG harmonic components can exploit the actual specificity and sensitivity only when performed over a wide frequency range explored with a good resolution, using low-distortion stimuli. In our opinion, the method presented here is a simple, effective solution to introduce some of the most recent and interesting results of neurophysiological and psychophysical research in the eye clinic.

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Erratum

SCHARFETTER, H., WIRNSBERGER, G.H., HOLZER, H., and HUTTEN, H. (1997): 'Influence of ionic shifts during dialysis on volume estimations with multifrequency impedance analysis', *Med. Biol. Eng. Comput.*, 35, pp., 96–102

In the above paper Fig. 5 was incorrect.

The correct figure is shown below.

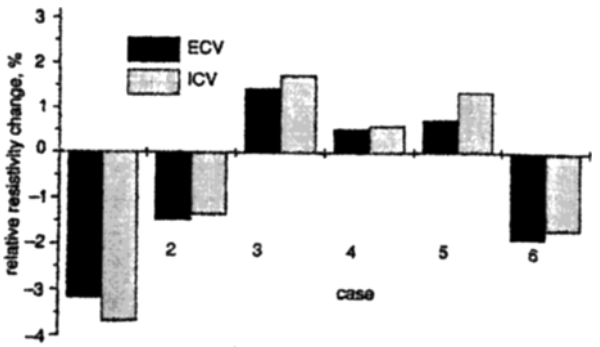

Fig. 5 *Resistivity changes between start and end of dialysis for all six patients*