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A versatile waveform generator for testing neuroelectric signal processors

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A multi-channel waveform generator was designed for testing neuroelectric signal processors. Smooth transient signals that resemble action potentials or evoked potentials are generated by a second order switched capacitor filter excited by brief rectangular pulses. The choice of an integrated circuit switched capacitor filter simplified the design by circumventing some of the disadvantages of conventional active filters. The waveform generator is versatile, with several signal parameters being independently adjustable from front panel controls: duration, waveshape, latency, amplitude and signal-to-noise ratio. The generator has been used for testing evoked potential acquisition and processing systems, for evaluating the effects of analog filters on evoked potentials and for testing systems designed to detect and classify trains of multi-unit action potentials.

Introduction

The processing of evoked potentials, nerve action potentials and motor unit action potentials may involve, among other things, analog and digital filtering, detection, synchronous averaging, artifact elimination, peak and latency determination, spectral analysis, pattern classification (e.g. Boston and Moller, 1985; Edin et al., 1988; Green et al., 1986; Mambrito and De Luca, 1984; McGillem et al., 1981; Schmidt, 1984; Vibert and Costa, 1979). Many systems have been developed for the acquisition and processing of such neuroelectric signals (e.g. Miskiel and Ozdamar, 1987; Quint et al., 1985; Smith and Wheeler, 1988; van den Akker et al., 1983; not to mention medical equipment manufacturers). Specially tailored input signals are needed to efficiently carry out the testing and calibration of those complex multi-channel systems. An example is the case of evoked potentials where one has to test the preprocessing stage (e.g. analog filters), the acquisition stage (e.g. timing hardware), the processing stage (e.g. software for artifact detection, synchronous averaging, digital filtering, peak detection, latency estimation) and the display-operator interaction software (e.g. signal scrolling, scale changes, cursor positioning). Conventional signal generators are not adequate testing devices because they do not generate the needed smooth transient multi-channel signals with independent controls for latencies, durations and waveshapes. A few specially designed waveform generators have been described in the literature and they can be divided in two classes. One class does not generate smooth waveforms, cannot be externally synchronized and presents great difficulties in adjusting duration and inter-peak latency while keeping the shape constant and vice versa (Blazek et al., 1975; Caballero et al., 1978).

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The circuits proposed in these papers consist of a number of monostable circuits connected in tandem, with the last one activating the first, and therefore forming an oscillatory loop. The output waveform is obtained by integrating a weighted sum of each monostable's output. The other class generates smooth waveforms stored in EPROM memories and hence they are characterized by fixed duration and fixed waveshape signals (Bach et al., 1984; Kaplan and Ozdamar, 1987). They give a faithful copy of one type of signal (e.g. a visual evoked response) and any change in waveform and/or duration requires another EPROM. However, in most practical cases the *exact* reproduction of specific waveforms (e.g. real-life visual evoked responses or motor unit action potentials) is not needed. What is usually required is the generation of smooth transient waveforms which approximate biological signals and with capabilities for easy adjustments of shape, duration and latency, so as to accommodate several different applications.

This paper describes an electronic device that generates multi-channel transient signals with front panel provision for latency, waveshape, duration and amplitude adjustments. The instrument is based on a switched capacitor filter complemented by digital and analog integrated circuits. It has been widely used in our laboratory for testing hardware and software being developed for the acquisition and processing of evoked potentials, motor unit action potentials and nerve action potentials.

Materials and Methods

Theoretical considerations

The main objective is to obtain a smooth "band-limited" transient signal with adjustable duration, waveshape and latency. A simple method to generate such a signal is to apply a brief pulse to the input of a second order low-pass filter. As is well known, the impulse response of such a filter is

$$h(t) = \frac{(A\omega_0)}{\sqrt{1-\zeta^2}} \exp(-\zeta\omega_0 t) \sin\left(\omega_0 t\sqrt{1-\zeta^2}\right)$$

$t \geq 0 \quad \text{and } 0 \leq \zeta < 1$

where A is the input impulse area, ω_0 is the undamped natural angular frequency of the filter and ζ is the damping ratio. The duration of each phase or half cycle is adjustable by changing ω_0 while the waveshape is determined by parameter ζ. For $\zeta \approx 1$ the impulse response is monophasic. As the value of ζ is decreased, more phases or peaks appear in $h(t)$. The latency may be varied by using a monostable to generate the input pulse. The desired ranges for ω_0 and ζ are 48–3930 rad/s and 0.1–0.5, respectively. The former was computed from the range specified for the duration of one phase of the impulse response (about 0.8–65 ms) while the latter was chosen subjectively by looking at the resulting waveshapes.

Conventional active filter implementations (i.e. using operational amplifiers) do not allow for the *independent* adjustment of both ω_0 and ζ. Another difficulty with an active filter realization is the fact that the output amplitude is very dependent on the value of ω_0. Actually, the peak amplitude is proportional to $A\omega_0$. For the desired ω_0 range the amplitude will vary about 82-fold. This means that any change in waveform duration will have to be followed by a readjustment in amplitude, which is undesired from a practical point of view.

The choice of a switched capacitor filter implementation avoids these difficulties associated with conventional active filters. In this type of filter realization, ω_0 is adjusted by changing a clock frequency (keeping ζ unchanged) while ζ may be varied by changing a resistance value (i.e. by using a potentiometer), without changing the value of ω_0. The problem of high sensitivity of the output signal amplitude on ω_0 is easily circumvented by designing a digital circuit that makes the input pulse area directly proportional to the clock *period* used for the switched capacitor filter. As ω_0 is directly proportional to the clock *frequency* (a property of the switched capacitor filter), it follows that the output signal amplitude is independent of ω_0. The output amplitude dependence on the waveshape parameter (ζ) is small, requiring only minor adjustments for ζ near its maximum value (0.5).

Hardware implementation

A circuit diagram of a single channel of the waveform generator is presented in Fig. 1. The

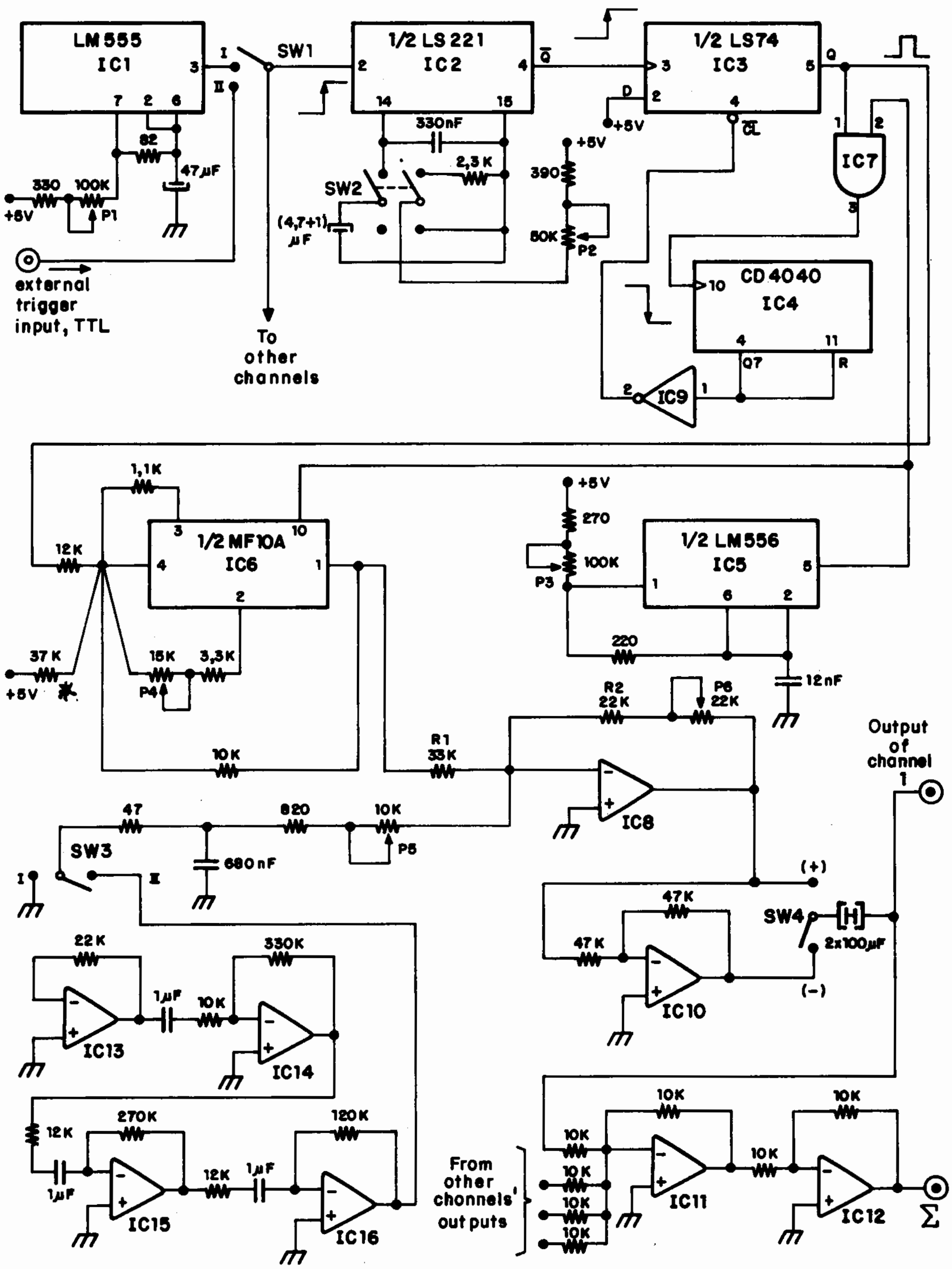

Fig. 1. Circuit diagram of one channel of the instrument for testing neuroelectric signal processing systems. Switch SW1 at position I (II) selects internal (external) synchronism. Switch SW2 (double pole, double throw) at the lower (upper) position selects the lower (higher) range of delays. Switch SW3 at position I (II) selects noiseless (noisy) waveform. Switch SW4 selects the output polarity. Potentiometers P1 and P2 set the stimulus rate and the post-stimulus delay, respectively. Potentiometers P3 and P4 allow the independent adjustment of ω_0 and ζ, respectively. Potentiometer P5 adjusts the signal-to-noise ratio when SW3 is in position II. Potentiometer P6 adjusts the output level. IC1: 1 LM555; IC2: 1/2 74LS221; IC3: 1/2 74LS74; IC4: 1 CD4040; IC5: 1/2 LM556; IC6: 1/2 MF10A; IC7: 1/4 74LS08; IC8,10,11,12: 1/4 TL074; IC9: 1/6 74LS04; IC13,14,15,16: 1/2 747. Resistance values are in Ω.

* It is probably better to use a trimpot (e.g. 100k) for offset adjustment.

components that are shared by all the channels are IC1, IC11, IC12, IC13, IC14, IC15 and IC16. The heart of the generator is composed of two parts: (i) integrated circuits IC3, IC4, IC5, IC7, IC9 which are responsible for the automatic adjustment of the input pulse area applied to the filter; (ii) integrated circuit IC6 which is a switched capacitor filter (MF10A from National Semiconductors) chosen to operate in mode 3 (Lacanette, 1985). The clock frequency ω_{SW} for switching the MF10A is generated by IC5. The proportion ω_0/ω_{SW} should be chosen as small as possible so that the switching frequency is much higher than the signal's bandwidth. In this project this proportion was chosen (using external resistors) 1/300. Much smaller ratios result in large DC offsets at the output and should be avoided. A short description of the whole circuit is given in what follows.

The integrated circuit number 1 (IC1) is an astable (555) that generates the internal stimulus synchronization for all the channels. The desired stimulus rate is adjusted by potentiometer P1. Switch 1 (SW1) selects internal or external synchronism (positions I or II, respectively). The delay from a stimulus trigger is adjustable by potentiometer P2 that sets the time constant for monostable IC2. It is necessary to switch capacitors (using switch SW2) to cover the desired latency range. After the desired delay time elapses, the output of the type D flip-flop (pin 5 of IC3) goes to logic level 1. This makes the 'and' gate (IC7) connect the clock signal generated by the second astable (IC5) to the input of a counter (IC4). When the final count $N = 64$ is reached, IC4's output at pin 4 goes high, thereby clearing the counter itself as well as flip-flop IC3. This disables the clock connection from IC5 to the counter. Only when a new stimulus pulse comes does the state of the circuit change again. In this manner IC3 generates a pulse whose average width is $(N-0.5)T_{SW}$ ($T_{SW} = 2\pi/\omega_{SW}$). This pulse is applied to the input of the switched capacitor filter (IC6) whose switching rate ω_{SW} comes from astable IC5. As $\omega_0 = \omega_{SW}/300$, the product of the input pulse width (proportional to area as amplitude is constant) with ω_0 is a constant equal to $2\pi(N-0.5)/300$. Hence, larger ω_0 (selected by varying potentiometer P3 of IC5) will result in a correspondingly smaller input pulse area, and vice versa, making the output pulse amplitude constant. The output pulse width from IC3 is not exactly $(N-0.5)T_{SW}$ due to the asynchrony between the timings of the delayed stimulus (output of IC2) and the clock from astable IC5. The pulse width value will lie in the range $(N-1)T_{SW}$ and NT_{SW} and hence the peak-to-peak time jitter referred to the average pulse width is $1/(N-0.5)$. The value chosen for N was 64 and therefore the pulse width jitter is 1.57% of the average, which causes no noticeable amplitude variability at the filter's output.

Amplifier IC8 (1/4 074) permits gain adjustments by means of potentiometer P6 as well as the addition of noise with a level adjustable by potentiometer P5. Switch SW3 in position I selects a noiseless waveform while in position II a noisy one. The noise source was built with four operational amplifiers connected in series (IC13–16). In the waveform generator that we built we used the same noise generator for all the channels. If for some special application the inter channel noise signals have to be uncorrelated then each channel should have a separate noise generator (two 747 Op. Amps. per channel). Switch SW4 selects the waveform polarity. Output Σ provides the sum of all channels' waveforms. If lower output signal levels are desired then one may increase the value of R1 and/or decrease the value of R2 (and P6). A lower signal level will be needed if the generator is applied to amplifier inputs instead of directly to A/D converter inputs or filter inputs.

The circuit requires only a ± 5 V power supply (for simplicity we used 7805 and 7905 regulators). The switched capacitor filter (IC6) and all the operational amplifiers use ± 5 V. All the other ICs use $+5$ V. Standard cares were followed regarding capacitor decoupling at the integrated circuits' supply pins and physical separation of the digital ICs from the analog in the printed circuit layout. The load impedances (i.e. input impedances of the systems under test) applied to the waveform generator output should be larger than 470 Ω. The generator's external trigger input should be at TTL levels.

The key features and specifications of the waveform generator are listed in what follows: (1) simplicity of circuitry; (2) portability; (3) simplicity of operation (parameter adjustment by means of potentiometers); (4) expandability to any number of independent channels; (5) internal or external synchronism; (6) generation of smooth multiphasic transient signals with adjustable durations and envelope decays; (7) possibility of adding adjustable levels of noise; (8) internal stimulus synchronism rates adjustable from about 0.3/s up to 40/s; (9) signal latencies (delays) from the stimulus synchronism adjustable from 0 up to 320 ms; (10) duration of each phase of the generated signal adjustable from about 0.8 up to 65 ms. The first three features mean that the instrument was designed to be inexpensive, easy to assemble and to use, and that it could be carried anywhere.

The specifications given above should satisfy many application needs but an examination of the circuitry shows that it is very easy to change or extend the specified ranges.

Results

Fig. 2 shows several output signals from the waveform generator. Fig. 2A shows seven waveforms having the same shape and amplitude but different durations. They were obtained by adjusting potentiometer P3 to seven different values covering the full range of ω_0. All other potentiometers (including P6 which controls output amplitude) were left unchanged for all seven waveforms. The oscilloscope gain and time-base were the same for all traces. The four channels of signals shown in Fig. 2B have different waveforms, latencies, durations, amplitudes and signal-to-noise ratios.

Fig. 3 shows the output signals from 5 different 4th order Butterworth bandpass filters that were excited by the same multiphasic input. Each input phase lasted about 0.8 ms and hence mimicked approximately the fast peaks in a brainstem auditory evoked response. The filters' high frequency cutoffs were held at 5 kHz while the low frequency cutoff frequencies were, from bottom to top, 3 Hz, 30 Hz, 100 Hz, 200 Hz and 300 Hz, respectively. Therefore, increases in the low-frequency cutoff caused decreases in latencies, sharp decreases in the first positive peak (P1) amplitude, decreases in the first peak-to-peak amplitude (P1, N1), increases in the next peak-to-peak amplitude (N1, P2), and so on.

The summed output Σ is useful if more complex waveforms are desired, as illustrated in Fig. 4. Fig. 4A could be viewed as a first approximation to an auditory evoked potential (the genera-

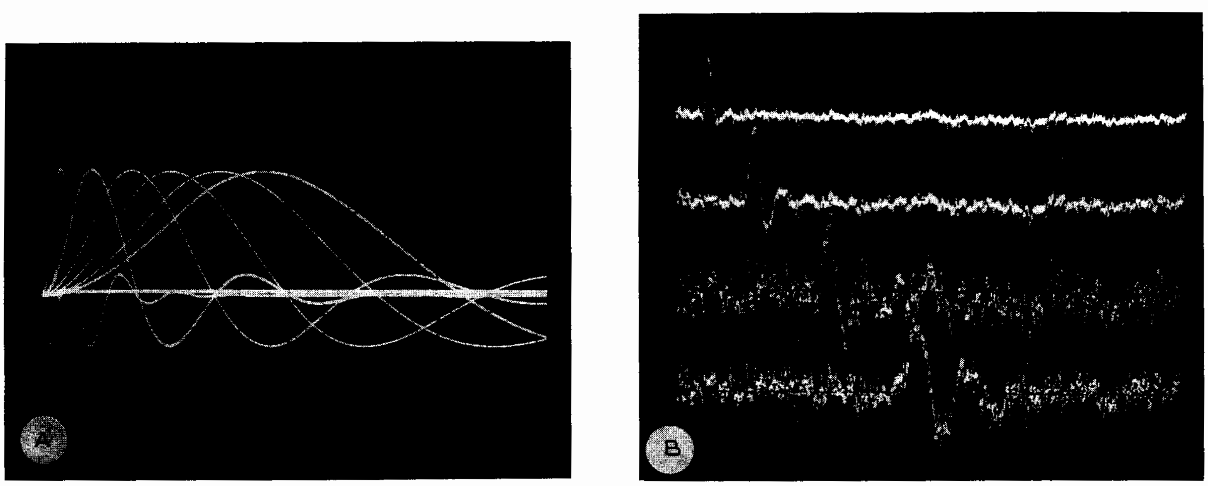

Fig. 2. Examples of ouput signals. A: a single channel's output was photographed for 7 different positions of the P3 potentiometer, covering the full range of waveform duration. The shortest peak or phase lasts 0.8 ms while the longest lasts 65 ms. Oscilloscope time-base setting is the same for all signals. B: 4 channels of waveforms with different shapes, durations, amplitudes, latencies and signal-to-noise ratios.

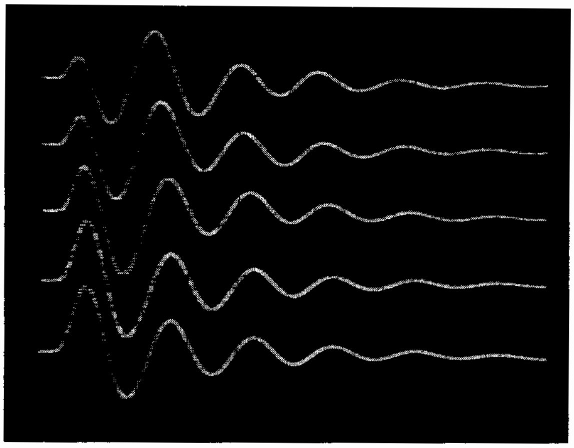

Fig. 3. Output from 5 different 4th order Butterworth filters excited by the same signal synthesized by the waveform generator. The high-frequency cutoffs were 5 kHz while the low-frequency cutoffs were, from bottom to top, 3 Hz, 30 Hz, 100 Hz, 200 Hz, and 300 Hz, respectively.

tion of additional peaks would require more channels than those available in our generator). Fig. 4B–D simulate 3 trains of 4 different action potentials. In the first (Fig. 4B), the action potentials are wide apart. In the second (Fig. 4C), the 4th action potential starts right after the 3rd but they are still quite distinguishable. In Fig. 4D there is a large degree of overlap between the 3rd and 4th action potentials making them quite difficult to discriminate.

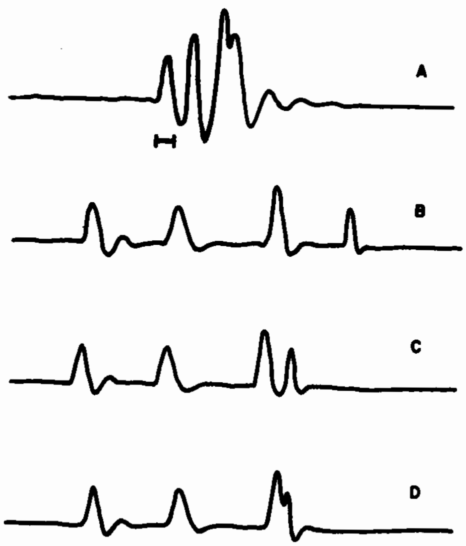

Fig. 4. Complex waveforms obtained from output Σ. A: a first approximation to an auditory evoked potential. B–D: 4 wavelets mimicking 4 different motor unit action potentials. In B there is no overlap, in C there is a small degree of overlap between the last two wavelets, in D the overlap is more pronounced. The time mark corresponds to 1 ms.

Discussion

Smooth transient signals, mimicking in essence evoked potentials or nerve and muscle action potentials, are extremely useful for testing neuroelectric signal acquisition and processing hardware and software, as well as for evaluating the effects of analog and digital filtering. The possibility of adding noise to the signals is helpful when testing systems running coherent averaging or detection/classification algorithms. The waveform generator, based on a switched capacitor filter, combines simplicity of use and assembly with versatility. The wide range of durations, latencies and waveshapes covered by the generator and exemplified in Figs. 2–4 is needed for applications ranging from muscle and nerve action potentials to evoked potentials of different origins and modalities.

One of the critical issues in evoked potential studies is the distortion caused by the preprocessing analog filters on the transient neural responses (Boston and Ainslie, 1980; Boston and Moller, 1985; Janssen et al., 1986). Interestingly enough, the results obtained in Fig. 3 are quite similar to many of those described in the literature for real life evoked potentials (see the 3 references above) hence suggesting that the signals synthesized by the waveform generator may be useful for providing first estimates of the effects of filtering (analog or digital) on evoked or spontaneous neural potentials. More complex signals (e.g. Fig. 4A), available from the summed output (Σ), would also be useful for testing filters, as well as, for example, for testing algorithms for automatic peak detection and latency measurement (Fridman et al., 1982). The signals of Fig. 4B–D would be very useful for testing detection/classification hardware and software for nerve and muscle action potentials (e.g. Edin et al., 1988; Mambrito and De Luca, 1984; Schmidt, 1984; Smith and Wheeler, 1988; Vibert and Costa, 1979). A difficult task found in such systems is the classification of overlapped discharges as exemplified in Fig. 4D. Controlled amounts of noise level could be added to the waveforms of Fig. 4 to mimic different experimental conditions.

The above described waveform generator should be useful to (i) neuroscientists and clinical neurophysiologists who want to check their system's or equipment's performance, operation and calibration, (ii) biomedical engineers and neuroscientists developing neuroelectric signal processing systems and algorithms, (iii) neurology and biomedical engineering instructors who need a practical signal generator to demonstrate modern electrodiagnosis methodologies and the operation of complex medical equipment, (iv) technicians who do corrective and preventive maintenance of this complex equipment.

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