Principles and Practice of Clinical Electrophysiology of Vision

Editors

JOHN R. HECKENLIVELY, M.D.
Professor of Ophthalmology
Jules Stein Eye Institute
Los Angeles, California

GEOFFREY B. ARDEN, M.D., PH.D.
Professor of Ophthalmology and Neurophysiology
Institute of Ophthalmology
Moorfields Eye Hospital
London, England

Associate Editors

EMIKO ADACHI-USAMI, M.D.
Professor of Ophthalmology
Chiba University School of Medicine
Chiba, Japan

G.F.A. HARDING, PH.D.
Professor of Neurosciences
Department of Vision Sciences
Aston University
Birmingham, England

SVEN ERIK NILSSON, M.D., PH.D.
Professor of Ophthalmology
University of Linköping
Linköping, Sweden

RICHARD G. WELEBER, M.D.
Professor of Ophthalmology
University of Oregon Health Science Center
Portland, Oregon

Mosby Year Book

St. Louis Baltimore Boston Chicago London Philadelphia Sydney Toronto

Mosby Year Book

Dedicated to Publishing Excellence

Sponsoring Editor: David K. Marshall
Assistant Director, Manuscript Services: Frances M. Perveiler
Production Project Coordinator: Karen E. Halm
Proofroom Manager: Barbara Kelly

Mosby-Year Book, Inc.
11830 Westline Industrial Drive
St. Louis, MO 63146

1 2 3 4 5 6 7 8 9 0 CL CL MV 95 94 93 92 91

Library of Congress Cataloging-in-Publication Data
Principles and practice of visual electrophysiology / [edited by]
John R. Heckenlively, Geoffrey B. Arden.
p. cm.
Includes bibliographical references.
Includes index.
ISBN 0-8151-4290-0
1. Electroretinography. 2. Electrooculography. 3. Visual evoked response. I. Heckenlively, John R. II. Arden, Geoffrey B. (Geoffrey Bernard)
[DNLM: 1. Electrooculography. 2. Electrophysiology. 3. Electroretinography. 4. Evoked Potentials, Visual. 5. Vision Disorders—physiopathology. WW 270 P957]
RE79.E4P75 1991 91-13378
617.7 1547—dc20 CIP
DNLM/DLC
for Library of Congress

27

Stimulus Devices

Ellis Loew

Any device capable of producing and delivering a change in light intensity to all or part of the retina can be used to elicit an electroretinogram (ERG). However, since ERG parameters are sensitive to stimulus characteristics, the type of stimulus device must be carefully chosen if meaningful ERGs are to be obtained. This is particularly true in the clinical setting where reliability and repeatability are of prime importance.

The choice of stimulus source will depend upon a number of factors, including (1) desired intensity operating range, (2) stimulus duration requirements, (3) triggering capabilities, (4) spectral characteristics, (5) stimulus repetition rate and duty cycle requirements, (6) stimulus structure type (i.e., uniform field or some type of pattern), (7) ability to interface to other optics, and (8) cost. Table 27–1 lists a variety of possible stimulus sources along with some of their relevant characteristics. The capacitor-discharge lamp (xenon flash lamp), light-emitting diode (LED), and cathode ray tube (CRT) are the most common stimulus devices in clinical usage. The other types, particularly the incandescent lamp, may be included in some clinical setups for providing background illumination or for facilitating other types of visual system testing.

A number of excellent reviews are available for those wishing to delve further into the various implementations of optical stimulators for the ERG.[1, 2, 4–6, 9, 13, 16] References cited in the text are illustrative, certainly not exhaustive.

XENON SOURCES

The xenon flashtube is the most popular stimulus source for routine clinical ERG. All commercial ERG systems come equipped with some type of flash head either built into a Ganzfeld illuminator or as a separate unit such as the Grass PS-2. The adoption of flash lamps as almost universal stimulus sources for clinical ERGs probably derives from their ease of use, simple control, essentially "white" light output, ability to operate at high flash frequencies, and compact design. However, it is far from the ideal stimulus and not suited for many types of special ERG tests.

In its basic form, a flash lamp is a length of glass tubing filled with an inert gas such as xenon that has electrodes sealed into each end. The passage of an electrical current through the tube causes the atoms of the gas to move to an excited state. In returning to the ground state, light is emitted at a wavelength determined by the energy difference between the excited and ground states. For inert gases like xenon, there are many allowed excited states, and thus the spectral output can be quite broad (Fig 27–1). The spectral distribution of the emitted light depends upon the gas(es) used, its pressure, and the current density. Xenon flashtubes with low fill pressures and medium operating current densities produce most of their light in the visible part of the spectrum, although appreciable energy is found in the infrared and ultraviolet. Output intensity is directly related to current density.

The energy for flash lamp operation is stored in a capacitor wired in parallel with the flashtube. This capacitor is charged to some dc voltage below the ionization potential of the gas by a high-capacity power supply. When a small amount of the gas is ionized by a "trigger" input (usually a high-voltage pulse applied to the lamp envelope), the capacitor discharges through the tube to supply the energy for light production. The time course of capacitor dis-

TABLE 27–1.
Sources of Visible Radiation

Incandescent lamps	Electrical current flowing through a filament causes it to heat and produce an approximate "black-body" spectral output. A halogen cycle is employed with a tungsten filament to allow operation at high temperatures without blackening of the envelope. The spectral range is from near-ultraviolet to infrared
Gas discharge lamps	Voltage above the ionization potential of the enclosed gas causes a current flow through the lamp. Recombination of charge pairs or a return to the ground state results in photon production. Spectral output is determined by the gas(es)
Fluorescent lamps	Similar to gas discharge lamps, but the interior surface of the lamp envelope is coated with a phosphor that absorbs photons produced by discharge and emits broadband light through fluorescence. Mercury is the common discharge gas. Spectral output is determined by phosphor
High-intensity discharge lamps	A gas discharge tube, usually mercury or sodium, having a construction allowing very high lamp outputs to be obtained. These are filled at high pressure, which broadens the spectral lines of the constituent gas. Output is a modified line spectrum
Radio frequency lamps	An incandescent-type lamp where a disk of tantalum carbide is heated indirectly by the absorption of radio frequency energy. This produces a very bright disk source having great spatial uniformity. They are used mostly in movie film printers
Photoflash lamps	A shredded metal, usually aluminum or zirconium, is burned in an oxygen atmosphere to produce a brief, very bright flash of light. The metal is ignited by a tungsten filament heated electrically. These are the familiar white or "Blue Dot" flash bulbs
Electronic flash lamps	Energy stored in a capacitor charged to a voltage below the ionization potential is allowed to flow through a gas ionized by a high-voltage trigger pulse. Xenon is the usual gas, and the spectral output is broad (see the text)
Glow-modulator lamps	These are gas discharge lamps having an electrode structure so that the emitting area is small. By controlling the current to the tube after "striking," the light output can be modulated up to 80% at high frequency. These were originally neon tubes used for producing the soundtrack on movie film. However, recently "white light" versions have been introduced
Light-emitting diode	Light produced by the recombination of charges at the interface of two semiconductor materials. The spectral output is determined by the energy state of the two semiconductors (see the text)
Electroluminescent lamps	Essentially a capacitor with a fluorescent dielectric separating its plates. Application of an ac signal to the plates causes the dielectric to glow. One of the capacitor plates is usually transparent. Its spectral output depends on the phosphors present in the dielectric

charge and therefore of the light output depends on the electrical characteristics of the lamp/capacitor circuit. In Figure 27–2 it is seen that as capacitance increases, peak intensity output increases as does flash duration. Note also that the light output is not constant during the flash interval but has exponential rise and fall times.

The intensity control switch on units like the Grass PS-2 functions by changing the value of the main storage capacitor across the flashtube. The values of the capacitors used by Grass yield flash durations varying from a few to several hundred microseconds. The rate at which a flash lamp can be operated depends on how fast the capacitor can be recharged by the power supply. At the highest intensity the Grass unit can operate reliably up to about 30 Hz. If a frequency above the limit imposed by the capacitor recharge time is selected, the most obvious sign is erratic firing of the flash lamp. However, even before erratic firing is seen, the intensity per flash will fall and become unpredictable since there has been insufficient time for a full capacitor

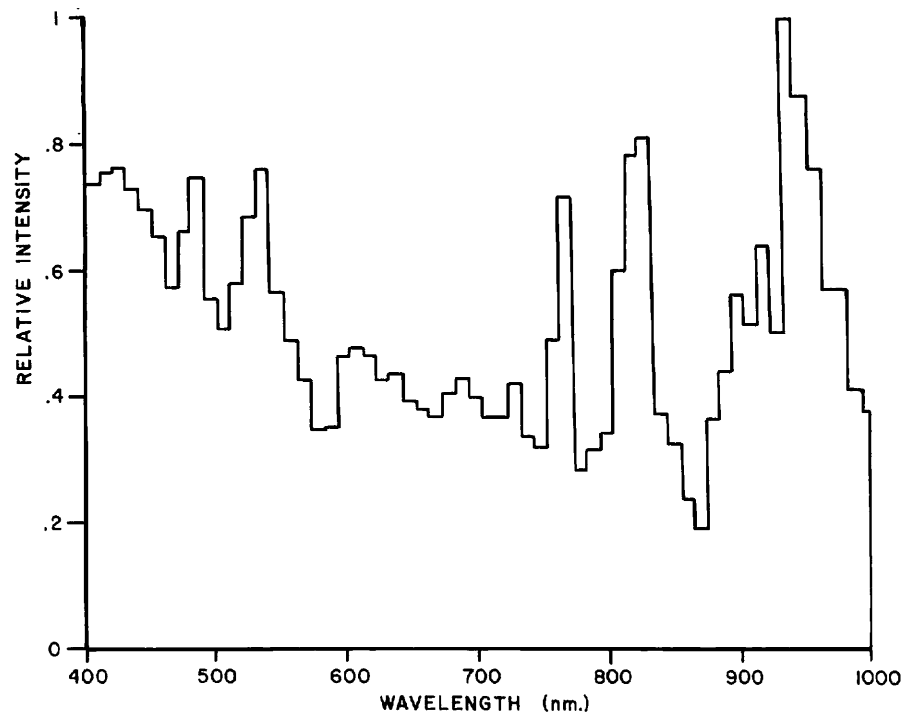

FIG 27–1.
Relative spectral energy output from a typical xenon flash lamp. The area under the curve is the total light energy output (candela-sec/joule) and is directly related to the energy stored in the discharge capacitor (joules). Note the large integrated energy above 800 nm. (Redrawn from Amglo, Inc, *Flashtube Engineering Manual,* 1969.)

charge before triggering a flash. Many scientific and photographic strobe units incorporate special circuitry to signal when the charging voltage between flashes has fallen into the "uncalibrated" zone. Circuits may also be present that prevent triggering before the capacitor is fully charged. This problem is most obvious at high intensity where one is dealing with large capacitors and long charging times. If operation at high intensity and frequency is anticipated, it is best to have the individual unit calibrated at these settings because component variation and age will greatly affect unit operation.

As mentioned above, xenon flashtubes are the most popular stimulus source for clinical ERG. Their main virtues are as follows:

1. Brief flash duration. This is useful for looking at fast transients such as the early receptor potential.
2. Broad spectral output. This makes the lamp useful for chromatic studies.
3. Electronic intensity control. The intensity can be controlled without the necessity of large, expensive, neutral-density filters.
4. Potentially high flash repetition rate. This is particularly relevant for critical flicker frequency (CFF) measurements.

In addition, they require no external shutters, are easy to interface with recording equipment, produce no heat when not "flashing," come in handy self-contained units, require no special knowledge to use, and are reliable. However, they are not ideal, and their ignorant use can lead to unreliable ERGs. The following is a list of shortcomings most relevant to clinical usage:

1. Large interflash output variations. Even small differences in charging voltage can have effects on lamp output. Component age is also a factor. Output variations are particularly prominent during multiple- and twin-flash operation.

2. High output in the infrared and ultraviolet. It is necessary to adequately filter the lamp to avoid damage to the eye due to "invisible" output.

3. Calibration difficulties. Because the flash is so brief, conventional radiometers cannot be used for intensity calibration. Special high-speed light meters must be used. "Cookbook" recipes for calibrating

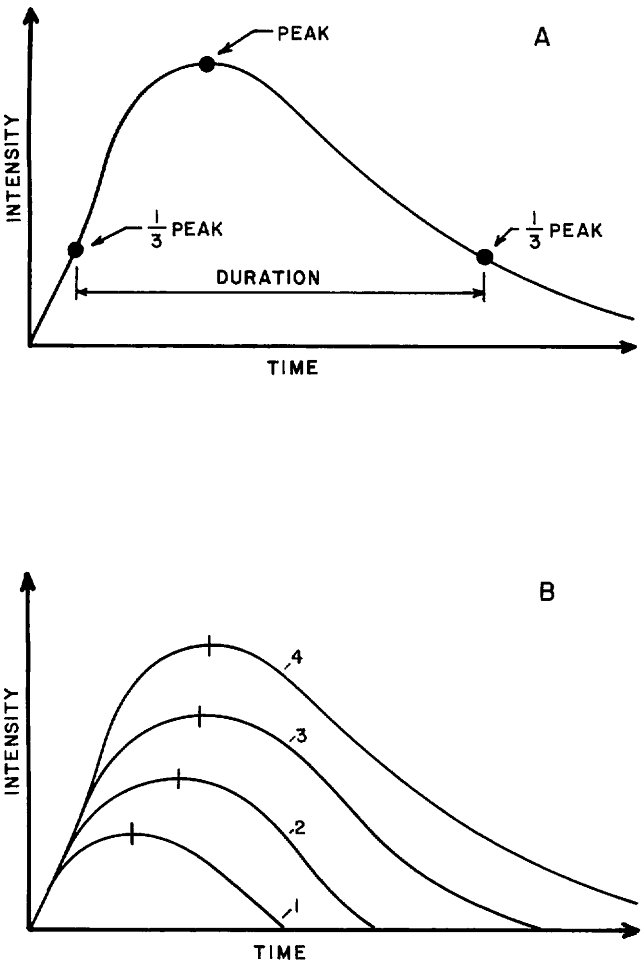

FIG 27-2.
Time course of the light output from a typical xenon flash lamp. **A**, this curve indicates the convention for specifying the flash duration. Note the exponential rise and fall times of the flash. These drive from the resistor-capacitor (RC) properties of the capacitor-discharge circuit. **B**, these curves depict the changes in flash intensity and duration as the value of the energy storage capacitor is decreased. This would correspond to changing the intensity control on the front of a Grass PS-2 photostimulator. Decreasing capacitance decreases the peak intensity and the flash duration.

Ganzfeld bowls have been described that utilize the integrating properties of slow amplifiers. These are only to be used under the *exact* conditions specified.

4. Poor lamp optics. The flashtubes most frequently used consist of a helical coil approximately 2.0 cm in diameter. This extended source makes it difficult to collimate or focus the lamp output for interfacing with other optics, filters, or light pipes.

5. Large interunit variations. The outputs from different Grass PS-2 units can vary as much as 10% even for "calibrated" systems. This makes strict comparisons between ERGs obtained in different laboratories difficult even if the same stimulus protocols are used.

6. Large electromagnetic artifacts. The high-voltage trigger and capacitative discharge through the lamp produce large artifacts that can saturate the input stages of very sensitive amplifiers if proper grounding and shielding practices are not observed. The high current density also produces a magnetic pulse that can couple to other components and cannot be prevented by using conventional Faraday shielding. For this reason, the headpiece containing the trigger transformer and flash lamp should be placed some distance from sensitive equipment and the patient.

There are several ways in which these shortcomings can be overcome. Obviously, proper placement and shielding can prevent serious artifacts from interfering with the ERG. It is also advisable to use neutral-density filters as opposed to electronic intensity control because this will minimize the problem of interflash variation. Some newer units are available with feedback control of the flash intensity. The system is identical to that used in high-quality "automatic" photographic flash units. The heart of the control unit is a quench tube placed in parallel with the flash lamp. When triggered, this tube shunts the capacitor current away from the flash lamp, thereby ending the flash abruptly. An external photodiode monitors the output of the flash lamp and triggers the quench tube when a predetermined light output has been reached. As with any piece of equipment, follow the instructions carefully, read all the disclaimers and tolerance figures, and above all, never assume that the "typical" values for intensity or duration given in the manual are those for your unit.

GANZFELD STIMULATION

Standardization of the clinical ERG requires not only a knowledge of stimulus source parameters but also adoption of a method for stimulating the retina. Assuming the light source is well characterized up to the corneal surface, uncertainties as to the actual stimulus intensity reaching the retina and its retinal location must be dealt with. Obviously, such things as pupil diameter and the presence of scattering cataracts will affect retinal illumination. Variations in ERG amplitude and waveform due to area effects (i.e., the visual angle subtended by the stimulus, scatter) can also be a problem. Pupillary effects can be eliminated by focusing an image of the source at the pupillary plane that is smaller than the pupillary diameter. This is called the maxwellian view and is used frequently with tungsten shutter systems for research ERG. However, unless high numerical aperture optics are used, only a relatively small area of the retina is stimulated by maxwellian systems. The area effect is best handled by stimulating the entire retina uniformly. This requires an extended source of uniform spatial intensity covering the entire visual field. A source of this type is called a Ganzfeld stimulator. The fact that the whole retina is stimulated uniformly tends to minimize the "smearing" effects that regional differences in stimulus intensity have on the ERG waveform. Ganzfeld responses have steeper a-wave slopes and more well defined peaks.[6]

Clinical Ganzfeld stimulators are often "homemade" or constructed from bowl perimeters of the "Goldmann" type, and in fact, some commercial perimeters may have flash stimulators for the ERG already built in. A Ganzfeld stimulator will also have provision for illuminating the surface with constant adapting backgrounds and for varying the intensity and wavelength of the adapting and stimulating lights either manually or by computer.[3] The quality of a Ganzfeld stimulator is measured by the uniformity of its luminance. Variations of less than 1% for the central 60-degree field are desirable.

In the absence of a bowl perimeter, there are still several ways of approaching a "Ganzfeld" condition. A good approximation can be had by placing Ping-Pong ball halves over the eyes and using a conventional stimulator. However, this can prove unwieldy if large Burian-Allen electrodes are used. It is also possible to make scleral shell or corneal contact lens electrodes (e.g., ERG-Jet) opalescent by "flashing" under a running stream of silica abrasive. In use, care must be taken to ensure that the lens totally covers the dilated pupil.[10] Placing a smaller extended source as close as possible to the corneal surface can also produce a Ganzfeld situation. This can be done by mounting LEDs on the recording lens[11, 12] or placing the end of a fiber light guide as close to the cornea as possible.

LOCAL STIMULATION FOR ELECTRORETINOGRAPHY

In many cases it is desirable to record the ERG from only a small region of retina, for example, the foveal region.[14] Since the corneal ERG measures a mass response, its magnitude will depend on the number of elements stimulated. The smaller the area stimulated, the smaller the recorded ERG. Signal-averaging techniques are used to overcome this difficulty. However, a more serious problem stems from an inability to ensure that a stimulus is limited to only a particular retinal region. One might think that providing a stimulus calculated to occupy 1 degree of visual angle would only stimulate the 1 degree of retina surrounding the fixation point. However, intraocular scatter causes an unknown amount of stimulation of other retinal areas. The common methods of handling this problem involve adapting out or raising the threshold of the retina surrounding the area of interest by using constant backgrounds. For example, a bright blue "Ganzfeld" background will adapt out the retina except for the macular region, where the yellow pigment absorbs the background before it can reach any photoreceptors. The absence of blue foveal receptors will further decrease the sensitivity of this region to the blue background. A yellow (i.e., minus blue) stimulus delivered against a blue background will yield an ERG reflecting activity of only the macular region. It is also possible to isolate retinal regions by moving a constant stimulus over a small part of the retina in the presence of a Ganzfeld adapting background. The total amount of light entering the eye and therefore the scattered component remain constant—only retinal position is periodically varied. There are several ways of implementing such a stimulator: by using LEDs, cathode ray displays, or mechanical scanners.

PRODUCTION OF COLOR STIMULI

Varying the color of the background and/or stimulus allows for stimulation of different chromatically sensitive retinal mechanisms or adapting them out. For example, eliciting a photopic ERG in the presence of a strong, red adapting background will provide information on the blue and green mechanisms unaffected by the red mechanism. Selective chromatic adaptation is the method of choice for measuring spectral sensitivity when using the ERG. Any contribution of the rods to the photopic ERG can usually be eliminated by using a yellow adapting background near the photopic threshold.[7]

In reporting data obtained with color stimuli, it is important to specify not just the apparent color (e.g., red, blue, etc.), but also the filter designations and the type of stimulus source. For example, similar yellow-appearing stimuli can be produced by filters such as the Wratten 9, which absorbs all light below 470 nm, and the Wratten 54, which only transmits the band between 500 and 600 nm. While perceptually similar, the ERGs obtained when using these filters may differ.

Filters

The options available for producing color stimuli are numerous, but filtering is the most realistic for routine clinical testing with flash lamp or tungsten stimulators. Filters are specified according to the shape of their transmission curve and the wavelength of the maximum transmission or the wavelength of 50% transmission, depending on filter type (Fig 27–3). Filtering is accomplished either by selective absorption or interference phenomena. Interference types offer better performance, but they are more expensive than absorptive types, particularly in the larger sizes. Absorptive types are available as glasses or as gelatin sheets (the Wratten type), the latter being the most cost-effective. Interference filters are normally calibrated by using collimated light at right angles to the filter surface. The use of an uncollimated beam will affect the bandwidth and/or filter maximum, as will using the filter at other than the normal angle. Filters specified for use at other angles and calibrated for uncollimated light are available from most optics houses.

The selection of filters is usually made directly from manufacturers' specifications or a compendium such as that of Wyszecki and Stiles[16] (note that only the first edition of Wyszecki and Stiles contains extensive filter information). However, several things must be kept in mind when using absorptive filters, particularly band-pass types. First, blocking of light outside of band-pass filters is usually only to density 2 or 3. With some light sources there may be enough spectral output in these out-of-band regions to stimulate photoreceptors. Second, many filters have windows far outside of the stated band pass that may be of concern. This is particularly true for the "red windows" present in most of the short-wavelength Wratten filters. Although leakages at long wavelengths may not be effective stimuli for the ERG, they may contribute to the measured output of a calibrating device and lead to false values for retinal illuminance.

Regardless of filter type, all have finite lifetimes and must be replaced at intervals determined by substrate material, hours of use, and wattage of the stimulus source. Unfortunately, there are no hard-and-fast rules for when one should replace filters. Sometimes simply looking through a gelatin filter will indicate bleaching or spatial deterioration. Other times the need for replacement may only be obvious when control ERG data start to look "funny." In any case, it is always a good idea to have spares of fre-

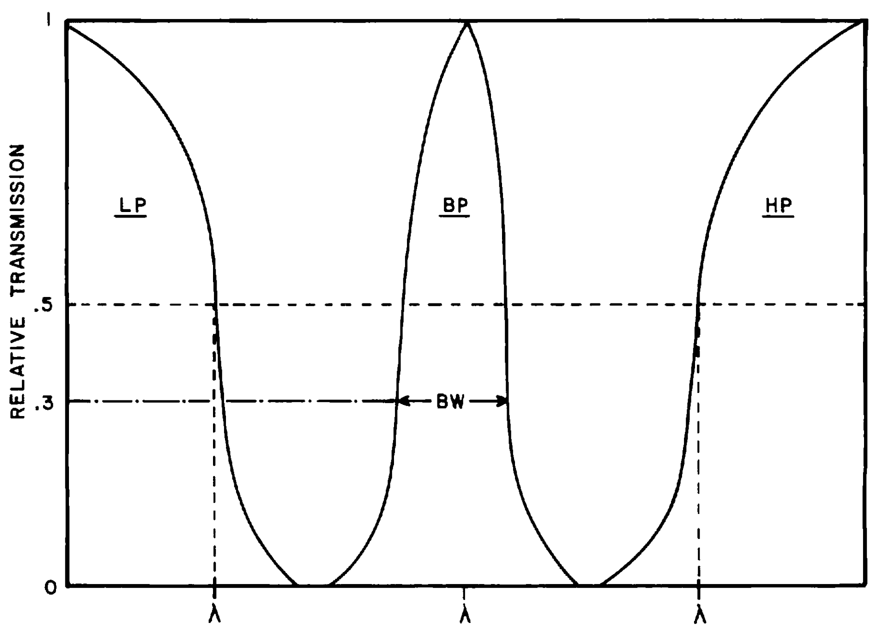

FIG 27–3.
Conventions for specifying color filters. Low-pass *(LP)* and high-pass *(HP)* filters are specified by the wavelength corresponding to 50% transmission. The slope of the filter function is an important parameter but is rarely specified. Band-pass *(BP)* filters are specified by the wavelength of the maximum transmission and by bandwidth *(BW)*.

quently used filters on hand at all times. Even when only "white" stimuli are desired, it is advisable to block radiation below 400 nm and above 700 nm from all broadband stimulus sources, particularly from flash lamps. A good filter combination for this purpose is an L-40 and HA-50 (Hoya Optical, Fremont, Calif). The glass window used by Grass on the PS-2 lamp housing does a fairly good job at filtering out the infrared but lets a substantial amount of near ultraviolet through and should be supplemented with the above filters or a similar combination.

DISPLAY TUBES

This class of stimulators includes devices capable of producing not only uniform, two-dimensional stimuli but spatial patterns as well. Most commercial units are based on some type of CRT, although some systems incorporate LED arrays or liquid crystal display (LCD) technology. (See Chapter 28).

General Description

All CRTs operate on the same basic principles. Electrons emitted from a hot cathode are collected and focused into a beam by electrostatic or magnetic lenses and accelerated toward an anode at high positive potential. The beam is allowed to strike a surface coated with a phosphor that emits light when bombarded by the electron beam. This light exits the tube through a transparent window. The intensity of light emitted by each surface element depends on the flux of electrons hitting the element (the beam current) and the phosphor efficiency. Many different phosphors are available that have different spectral outputs and persistance. The phosphor used in monochrome video systems is designated P4 and is broadband white with medium-short persistance. The beam current is controlled by varying the potential on a number of grid elements placed in the path of the electron beam. The beam current can be modulated at high frequencies and follow any waveform. In its simplest mode, the electron beam can be made to "flood" the entire anode surface to produce a uniform stimulus field. However, the beam currents available from general-purpose displays are not sufficient to provide useful stimuli of more than a few degrees with this method. Rather, a finely focused electron beam is rapidly swept across the anode surface in a raster mode. This is accomplished by feeding sawtoothed waveforms of appropriate frequency to sets of plate electrodes within the tube (electrostatic deflection) or to appropriately placed electromagnets (magnetic deflection). When the time needed to successively scan the anode (the frame rate) exceeds the critical fusion period, no flicker is observed. Any general-purpose oscilloscope can be pressed into service as a visual stimulator, but most installations use standard video monitors as output devices. The most common video frame rates are 50 or 60 Hz, depending on the country, although many computer-based systems use "nonstandard" frame rates as high as 250 frames per second.

The chromatic, temporal, and spatial output of a CRT are also determined by phosphor type and spatial uniformity and the quality of the electron optics. A number of correction collars are provided on most CRT displays to make it possible to adjust the raster for maximum uniformity of light output and linearity of scanning. Electronic controls for these purposes are also often provided. In any case, for critical work is it advisable to have the CRT calibrated for output by a metrology lab because the equipment needed for this process is quite expensive.

Production of Patterns/Contrast

CRT displays are ideal for producing spatially and temporally variable patterns. All that is required is some way of selectively altering the beam current at known times during the generation of a frame. By varying the magnitude of the beam current, different brightnesses can be produced within the pattern, thereby altering contrast. Patterned stimuli are becoming increasingly important as more becomes known about the pattern ERG (PERG) and have always been the stimuli of choice for visual evoked response (VER) testing.

Early pattern generation systems used conventional laboratory oscilloscopes with various waveforms fed into the x-, y-, and z-axis inputs. Random and raster displays could be generated at very high frame rates. These systems were initially analog, but later versions used digital technology and computer control. Standard video monitors were also used as output devices. These differ from oscilloscope-based systems in that the x- and y-axis were driven by internal sawtoothed oscillators to produce a raster. Control electronics only had to generate a synchronous signal and a beam-modulating (video) signal. The monitor was often modified so that the polarity of the video signal could be reversed by an external signal. In this way the screen brightness was controlled, and the pattern could be "flipped" with very simple external circuitry. This same circuitry provided the synchronizing signals for the data acquisition system. Any kind of pattern could be used, although a checkerboard one was common. More extensive circuitry was needed for producing contrast variation within a single frame. With the introduction of cheap digital video controller chips, it became more economical to store various patterns and intensity information in digital memories that were read out sequentially as the electron beam traversed the screen. The use of digital memories allowed for nonstandard frame rates and much more control over stimulus parameters. Again, these were essentially "hard-wired" systems that were not necessarily computer based. Modern CRT-based optical stimulators are software driven and offer the experimenter total control over all stimulus parameters. All geometrical patterns are available and can be drifted and modulated as desired. Color is also a variable that can be easily controlled. The stimulus software is often integrated with a data acquisition system running on the same computer so that a total visual testing station can be realized.[15]

The major problems with CRT-based stimulators are the ever-present scan lines, limited resolution, and an inability to produce a real "black," which limits contrast potential. Resolution is determined by the beam spot size, the video bandwidth of the amplifiers, and the number of horizontal scan lines in the raster. These factors are always improving but still do not rival film for resolution. Even the best black matrix CRTs can still be gray when the beam is turned off. This can be partially compensated for by surrounding the CRT with an illuminated white screen; this has the effect of making the screen appear darker (a trick used by Sylvania in their "Halo" TVs of the late 1950s and early 1960s). However, attaining a real black is still difficult.

Production of Color

By changing the phosphor or using a mixture of phosphors, a CRT can be produced that has almost any color output desired. Table 27–2 lists the most common phosphors available. Odd phosphors such as P16, which produces ultraviolet light, are special order items, although amber and green are now very common due to their use as computer video display terminals (VDTs). The phosphors in these CRTs are homogeneous, continuous layers across the screen face and should not be confused with the dot or stripe types used with color television systems. In some cases it is possible to get multiple colors from these CRTs by layering phosphors having different efficiencies or thresholds and varying the beam current appropriately. However, the range of colors available from such systems is very limited and usually not suitable for determining spectral sensitivities or for implementing special chromatic ERG tests.

The common color TV monitor is based on additive color mixing of the light output from three phosphors (red, green, and blue) arranged as a regular array of dots or stripes across the CRT face. The CRT structure produces three beams, each of which hits only one of the phosphor types. To ensure purity, each phosphor element is surrounded by a black matrix, and a mask limits excitation to only one phosphor element of each color at a time. Figure 27–4 shows the region of human color space reproducible by using a type P22 phosphor trio. Note that while almost all hues can be reproduced, saturation is limited in some spectral regions. However, the system is still quite useful for color vision testing.[8] White is obtained when the effective light output from each phosphor is the same. This will require

TABLE 27–2.
Typical Screen Phosphors for Cathode Ray Tubes

Phosphor	Output	Persistence	Use
P1	Green	Medium	Oscilloscopes
P2	Yellow	Medium	Oscilloscopes
P4	White	Medium-short	Picture tubes
P7	White, yellow	Short, long	Two-layer screen
P11	Blue	Medium-short	Oscilloscopes
P12	Orange	Long	Oscilloscopes
P14	Blue, ultraviolet	Short, long	Two-layer screen
P15	Green, ultraviolet	Very short	Flying-spot scanner
P16	Purple	Very short	Flying-spot scanner
P22	Red, green	Medium	Tricolor monitors; phosphor dots for each color

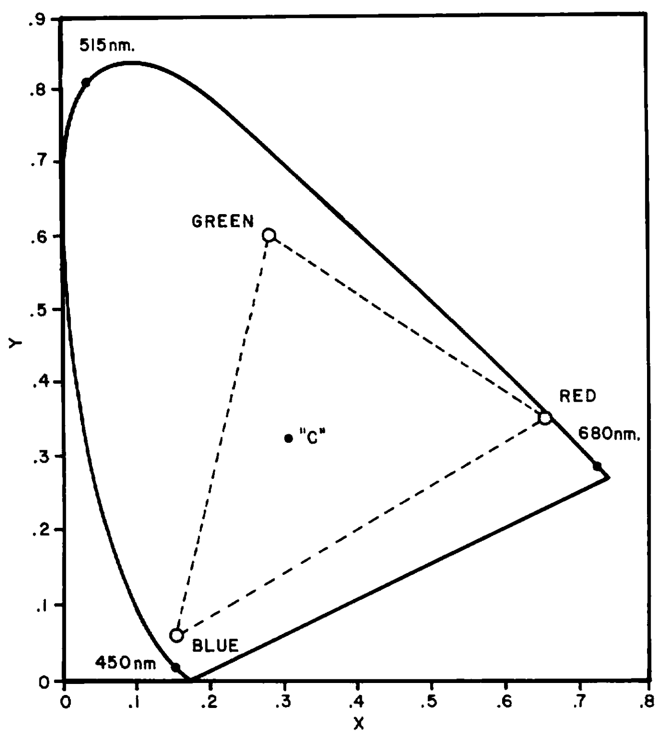

FIG 27–4.
The human CIE 1931 chromaticity diagram shows the locations of the blue, green, and red P22 phosphors used in conventional color monitors. The triangle formed by the *dashed lines* joining the three phosphor locations, as specified in JEDEC publication 16-C, defines the region of CIE color space available when using these color monitors. The *filled circles* at 450, 515, and 680 nm on the spectral locus are the wavelengths of the maximum phosphor emission. The *filled circle* at "C" is the location of the spectral illuminant "C" used for white balance adjustment.

different beam currents for each of the phosphor types due to differences in efficiency. In modern color TVs the beam-current ratios giving white are 0.3(R) + 0.59(G) + 0.11(B). This ratio is maintained throughout the gray-scale tracking range of the monitor.

The modern, computer-based color stimulator usually uses a monitor having separate R, G, and B analog inputs. Variation of the input signal from 0.0 to 0.7 V increases the light output linearly over an intensity range determined by the contrast and brightness controls. The contrast control varies the slope of the signal-to-brightness curve and sets the black level. The brightness control sets the upper limit for the beam current. The signals to the three channels come from a video display board within the computer that has three separate digital-to-analog converters. The number of colors available through mixing of these three signals is determined by the number of bits allocated for color specification. The gray scale is almost always 8 bits deep (256 gray levels).

The greatest problem with color CRTs is maintaining color purity across the tube face. Purity degradation results when one color "beam" does not excite the entire phosphor element or hits neighboring elements of a different "color." This is easily spotted with a hand lens and is most obvious at the tube edges. The electronic optics in modern systems have numerous controls for purity, but unless special equipment is handy, adjustment should be left to experts. It is also important to place the monitor some distance from other electronic equipment because external magnetic fields can destroy color purity.

It must never be forgotten that the principles underlying the operation of multiphosphor color monitors/TVs derive from the Commission International de l'Eclairage (CIE) standard observer. In the situation where one is using a color monitor stimulator on a color-defective human or nonhuman subject, all concepts of screen color and brightness must be reevaluated.

REFERENCES

1. Armington JC: *The Electroretinogram* New York, Academic Press, Inc, 1974, p 478.
2. Crawford BH: *Techniques of Photostimulation in Biology.* New York, Elsevier Science Publishing Co, Inc, 1968, p 317.
3. Diprose GK, Smith MJ: Computer-controllable variable-intensity Ganzfeld stimulator for electroretinography. *Med Biol Eng Comput* 1985; 23:496–497.
4. Fishman GA: *The Electroretinogram and Electro-oculogram in Retinal and Choroidal Disease.* Rochester, Minn, American Academy of Ophthalmology and Otolaryngology, 1975, p 45.
5. Fricker SJ: Electrical responses of the visual system. *Int Ophthalmol Clin* 1969; 9:851–1105.
6. Gouras P: Electroretinography: Some basic principles. *Invest Ophthalmol Clin Sci* 1970; 9:557–569.
7. Gouras P, Mackay CJ, Ivert L, Mittl RN, Neuwirth J, Eggers H: Computer-assisted spectral electroretinography in vitrectomy patients. *Ophthalmology* 1985; 92:83–90.
8. Gündüz K, Arden GB, Perry S, et al: Color vision defects in ocular hypertension and glaucoma: Quantification with a computer-driven color television system. *Arch Ophthalmol* 1988; 106:929–935.
9. Henson DB: *Optometric Instrumentation* London, Butterworths, 1983, p 244.
10. Kooijman AC: The homogeneity of the retinal illumination is restricted by some ERG lenses. *Invest Ophthalmol Vis Sci* 1986; 27:372–377.

11. Kooijman AC, Damhof A: A portable ERG system with an automatic driven LED ganzfeld stimulation contact lens. *Ophthalmologica* 1981; 182:224–228.
12. Kooijman AC, Damhof A: A tricolor light source for stimulation and adaptation in electroretinography. *Doc Ophthalmol* 1986; 63:195–203.
13. Krill AE: *Hereditary Retinal and Choroidal Diseases, vol 1*. New York Harper & Row Publishers, Inc, 1972, p 354.
14. Vaegan, Billson F, Kemp S, Morgan M, Donnelley M, Montgomery P: Macular electroretinograms: Their accuracy, specificity and implementation for clinical use. *Aust J Ophthalmol* 1984; 12:359–372.
15. Weinstein GW, Arden GB, Hitchings RA, Ryan S, Calthorpe CM, Odom JV: The pattern electroretinogram (PERG) in ocular hypertension and glaucoma. *Arch Ophthalmol* 1988; 106:923–928.
16. Wyszecki G, Stiles WS: *Color Science*. New York, John Wiley & Sons, Inc, 1967, p 628.