Principles and Practice of Clinical Electrophysiology of Vision

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58

Measurement of Contrast Sensitivity

Geoffrey B. Arden

DEFINITION OF CONTRAST

If a visual stimulus varies in intensity, either in space or in time, it is possible to define a maximum and minimum intensity. The ratio between these intensities is known as contrast. If the output of a source changes from I_1 at t_1 to I_2 at t_2, the contrast is

$$\frac{(I_1 - I_2)}{(I_1 + I_2)}$$

This measure of contrast is often termed *modulation*. It is evident that the maximum value for contrast is 1.0 when $I_2 = 0$. A similar definition can be used when contrast is measured in a complex spatial scene. Sometimes, however, if the image consists of a single edge, the contrast is taken as $\Delta I/I_{avg}$, where averaging over the entire image occurs.

FLICKER AND GRATINGS

In visual science, it is often desirable to use stimuli that are repetitive in space or time: a simple example is the repetition of a flashing light. If one views a homogeneous field that alters in this way, it appears to flicker, and this is an example of temporal luminance contrast; if a repetitive pattern of varying luminance is seen (for example, a series of stripes), then the pattern can be described in terms of spatial luminance contrast. A stimulus can have both temporal and spatial contrast, for example, a pattern of vertical stripes can drift horizontally, the darker and lighter portions can be rhythmically interchanged (pattern reversal), or the *pattern* can be made to appear and disappear from a uniform background. Temporal and spatial color contrasts—without luminance changes—can also be produced. Analysis of visual performance is then reduced to determining the minimum contrast or contrast sensitivity associated with a stimulus that has given spatiotemporal (or color) properties. Chapters 29 and 52 in this book deal with the mathematical specification of stimuli in time and space, and Chapters 27 and 28 describe methods whereby such stimuli may conveniently be produced. The theory of threshold determination is discussed in Chapter 56. This introduction assumes that the changes are simple, repetitive, and sinusoidal.

TEMPORAL CONTRAST

It is evident that temporal contrast sensitivity varies with the temporal frequency changes of the object. Detection of objects is usually best at intermediate frequencies and reduced at higher and lower frequencies. The "low-frequency falloff" can only be seen with sinusoidal temporal changes. Likewise, if temporal frequency change is too fast, the object appears not to change at all. The frequency at which this occurs is the flicker fusion frequency. Familiar examples of objects that change so rapidly in time that they appear continuous are the images on TV or cinema screens. All parts of our retinas do not have similar capabilities: the flicker from a TV, which is invisible or nearly invisible with foveal viewing, can be readily seen with the peripheral retina. Also, the

ability to see flicker depends upon a number of other parameters. The cinema image is renewed less frequently than that of a TV, but the flicker is less obvious because the screen luminance is lower.

The exact form of temporal contrast sensitivity was first investigated by DeLange,[6] and the set of curves describing the behavior of the visual system (Fig 58–1) are often called DeLange curves. Note that the dependent variable is retinal illumination.[10] At low illuminations where rods subserve vision, only low temporal frequencies can be seen. The performance of the photopic system improves up to high retinal illuminations. There are irregularities at intermediate frequencies due to rod-cone interactions (see Chapter 59). The frequency at which 100% modulated stimuli cannot be distinguished from constant illumination is the flicker fusion frequency.

Temporal contrast sensitivity (like any form of contrast) is determined by how far the modulation of the stimulus can be reproduced by the photoreceptors and the intermediate neurons. The membrane potential of photoreceptors increases in illumination and decreases in darkness. The modulation of the potential depends not only upon the rate of change of potential at the onset of a flash but also upon the rate of recovery. Thus, for weak flashes, rods are "slower" than cones. For intense flashes, rods can respond very quickly to increases of illumination, but the recovery is very slow, and this is the reason why flicker becomes invisible in photopic conditions at low temporal frequencies. In cones, the recovery is much faster, so higher flicker rates can be transmitted. The highest frequency of stimulation that can be detected without attenuation of the signal (the characteristic frequency) is a convenient measure of the temporal response characteristics. In bipolar and ganglion cells, the characteristic frequency is higher than for cones. Thus diminution in flicker fusion frequency can be due to postsynaptic mechanisms as well as photoreceptor disturbance. An important instance is the recent finding that primate blue cones respond with the same dynamics as do red and green cones. The fact that the blue "channel" can only respond slowly has been well documented by psychophysicists, but this must be a function of postsynaptic mechanisms. The fusion frequency of retinal mechanisms is higher than that of higher cortical mechanisms. Thus, electroretinograms (ERGs) may follow flicker rates above psychophysical fusion frequency.

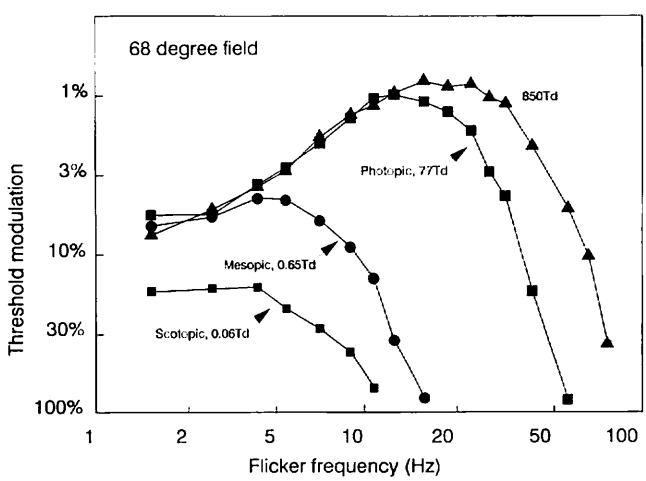

FIG 58–1.
Threshold modulation of a sinusoidally modulated light, as a function of temporal frequency. Note the logarithmic scales. The "low frequency fall off" is exaggerated, and the frequency of maximum sensitivity is elevated, due to the very large field size. (After Kelly.[10])

SPATIAL CONTRAST

Spatial contrast has attracted more interest than has temporal because the ability to resolve a pattern of high spatial frequency, i.e., a grating consisting of a series of fine lines, bears an obvious relationship to the common clinical test of visual acuity. In practice, no one would replace optotypes with fine gratings, and it is worthwhile discussing why. Optotypes are of course familiar. More importantly, differentiation of letters is a very powerful psychophysical tool: a "26-way forced-choice test." If the patient is asked to discriminate a grating from a uniform field, either we have to accept his estimate or else ask if the grating is vertical, horizontal, or oblique; this is a far less discriminative test. A "bell-shaped curve" relates spatial frequency to contrast threshold (Fig 58–2). For 2 to 4 cycles per degree, a contrast of 0.5% or even less may be detected; at the upper frequency limit (approximately 30 cycles per degree), a contrast of 100%—black on white—is required. Only this one point is determined in conventional measurement of visual acuity, and therefore nearly the whole spectrum of spatial vision is not detected by routine clinical examination. Figure 58–3 shows various types of contrast sensitivity functions that occur in association with a loss of the ability to see high spatial frequencies. Panel A shows the effect of minimal ametropia: only high-frequency vision is affected. However, a loss of contrast sensitivity may occur for every spatial frequency (panel B), and then visual discrimination is more severely impaired. In some form of cataract, only low-spatial frequency vision may be affected: then the patient will complain of impairment in his vision although visual

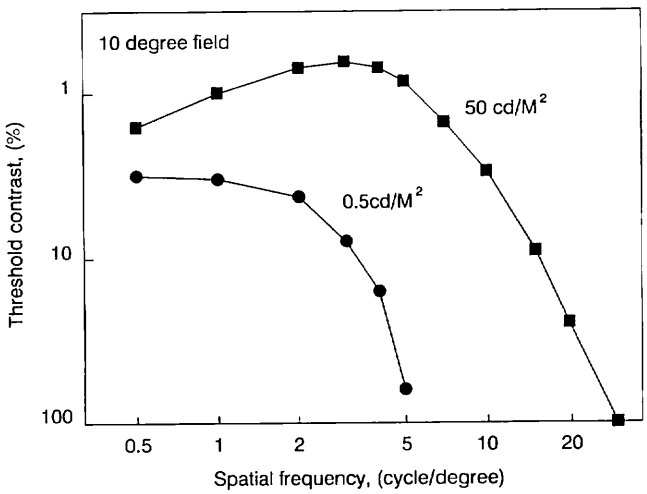

FIG 58–2.
Contrast sensitivity as a function of the spatial frequency of the sinusoidal grating. Scotopic contrast sensitivity is considerably worse than at 0.5 cd/M^2. (After Arden.[2])

acuity is normal. Therefore it is well worthwhile testing contrast sensitivity, providing this can be done quickly and simply. At low spatial frequencies, the contrast on the retina is not reduced by optical blur; therefore, if contrast sensitivity is reduced for such targets, either complex abnormalities (such as cataracts) are present, or there must be neurophysiological damage to the visual pathway. Another virtue of determining contrast sensitivity is that at low spatial frequencies the image covers a portion of the retina that is much larger than the fovea and, especially if a grating is used, detection depends upon the operation of the extramacular retina.

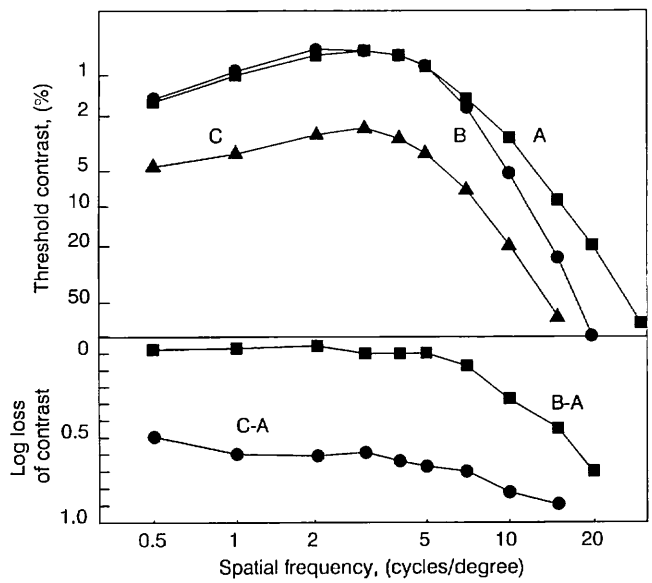

FIG 58–3.
Pattern of loss of spatial contrast. *Upper panel*, normal result, *B*, contrast loss at higher spatial frequencies such as occurs in minimal ammetropia. *C*, loss at all spatial frequencies, such as occurs in cataract. *Lower panel*, although visual acuity, the cut-off spatial frequency at 100% contrast or a higher contrast (e.g., 10%) is not greatly different between *B* and *C*, the subjective visual disturbance is quite different, as shown by the visuograms, *B*–*A* and *C*–*A*. (After Arden.[2])

It is easy to become too enthusiastic about the need for measuring contrast sensitivity, and it must always be remembered that defects in acuity are related to foveal damage and that, in practice, this is usually much more important to the patient than anything else. So great is the foveation of the visual system that a loss of low–spatial frequency sensitivity in practice indicates foveal damage, unless specific measures are taken to test the peripheral retina. Thus (see below), contrast sensitivity may appear to be normal in patients with defects in the peripheral field unless peripheral retinal contrast sensitivity is measured. Also, measurement of the cutoff spatial frequency with gratings of relatively high contrast, for example, 10% (see Chapter 57), is unlikely (except in special cases) to provide useful clinical information. Testing in this manner is sometimes described as measuring "grating acuity." In this author's view, it should be abandoned, especially since there are now adequate means of rapidly assessing contrast thresholds. Furthermore, not all visual defects lead to a loss of contrast sensitivity. In amblyopia contrast sensitivity is often quite good, even though the ability to read and recognize letters is poor: contrast sensitivity is determined by the retinal mechanisms, while the cortical analyzers of more complex functions suffer from an added disability.

MEANS OF PRODUCING STIMULI FOR TESTING CONTRAST SENSITIVITY

Temporal contrast sensitivity is best measured by equipment with electronic control of light intensity, and for most instances, the light-emitting diode is adequate since it is simple to control and provides a high source brightness. In applications where high spectral purity is required, light from a conventional optical system can be passed through filters or a spectrometer and then gated by a flicker wheel, with profiles cut to ensure sinusoidal output, or by using variable filters. Rotating Polaroids can also be employed, although a "cosine-squared" relationship results; electronic means of obtaining intensity variation can also be obtained with CROs, liquid crystals, or composites such as PZLT.

Spatial contrast sensitivity is often tested with gratings, which should be of sinusoidal profile.

These may be produced electronically, and various systems are commercially available (see Chapter 27). They produce the best results but are in general not mobile and are expensive. Alternatively, such gratings may be photographed and printed. Various versions of such tests exist: the best is backlighted, so contrast can be determined accurately and does not vary with ambient illumination. Near-vision and remote versions of such tests are available. Various low-contrast optotypes have also been described. These have certain advantages (see above), but the number of contrast levels are usually limited, and the letters are not filtered. While such tests may be adequate for spatial frequencies higher than that for maximum sensitivity, they will not do for lower frequencies. This can be checked by any myopic user: the visibility of the optotype should be unaffected by a spectacle correction.

METHODS OF TESTING

Electronic test methods, often computer driven, can incorporate sophisticated psychophysical paradigms. "Forced-choice" techniques are preferable. When a number of spatial frequencies are to be tested, they should not be measured in order of ascending or descending frequency to avoid fatigue or learning effects. The speed of making measurements is often of practical importance in the clinic. For this reason, techniques used in laboratories—ascending ramps, receiving operator curves, random blocks—are rarely employed. Modified binary search routines (MOBS) with "quick and dirty" algorithms for threshold determination are widely employed.

CLINICAL RESULTS

Temporal Frequencies

There are not many references to disease states in the literature. Responses are abnormal in retinitis pigmentosa and hypertension,[3, 16, 18, 19] optic nerve disease,[8] and cerebrovascular insufficiency. A recent review article by Tyler summarizes the results.[15]

Spatial Contrast Sensitivity

In many conditions, the patient's capability may be reduced below what is expected from visual acuity as a result of additional low-spatial frequency loss, and this has been described by numerous authors.[7, 9, 11–14, 17] Contrast sensitivity has also been used to diagnose eye diseases ranging from the corneal edema resulting from contact lens wear to glaucoma. References are to be found in recent reviews.[1, 2, 4]

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