Principles and Practice of Clinical Electrophysiology of Vision

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The d-Wave

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Chester Karwoski

The d-wave is a positive-going initial deflection in the electroretinogram (ERG) at light offset. This positive deflection is characteristic of the photopic ERG. In the scotopic ERG, the initial deflection at light offset is negative going, and (in mammals) it appears to be the offset of PII.[2, 6] Although positive d-waves have been described in the scotopic ERG of some species, they are probably not true d-waves. For example, in amphibia, Tomita[12] has argued that the rod-specific positive "d-wave" has a long latency and is probably the e-wave instead (see Chapter 13). Similarly, in cats, as described for mammals below, Brown[2] has pointed out that positive deflection occurs too late to be a true d-wave.

Although the d-wave is present in vertebrates from amphibians to mammals, it has received less study than the prominent components at light onset (a- and b-waves). In part, this may be because the d-wave is small in mixed retinas that have more rods than cones. In animals where the d-wave is prominent, it simply may be because vision researchers have traditionally presented light flashes rather than dark flashes. Nevertheless, there is some information regarding its origin, and this is discussed here separately for cold- and warm-blooded species.

In *cold-blooded species,* the d-wave is positive going when recorded on the cornea or in the vitreous and negative going when recorded in the distal half of the retina (Fig 12–1). This depth profile is compatible with the d-wave representing the photoreceptor off-response. Furthermore, many studies have shown that photoreceptors can contribute to the d-wave since a significant extracellular receptor potential can be recorded after postreceptoral neural activity has been pharmacologically blocked, e.g., in the frog[14] and the mud puppy.[11] However, results from these latter studies agree that cells postsynaptic to the photoreceptors also make a major contribution to the d-wave.

Dick[4] and Stockton and Slaughter[11] present data supporting the idea that the d-wave is generated by K^+ spatial buffer currents in Müller cells and that these currents are initiated by a light-evoked increase in $[K^+]_o$ that is caused by activity in horizontal cells and/or in hyperpolarizing bipolar cells. The theory is supported by the observation that Müller cells show a depolarizing off-response.[10] However, a direct contribution from horizontal cells and from hyperpolarizing bipolar cells has not been excluded.

A depth profile of the d-wave in the frog (see Fig 12–1) shows that this response has a relatively long rise time and peak time in the proximal retina but has a short rise time and peak time in the distal retina.[14] It is possible that the slower component is due to Müller cell activity whereas the faster component arises from the photoreceptors. The specific contribution of each of these processes to the corneal ERG of amphibians remains uncertain.

In *mammals,* the d-wave also is a positive deflection at light offset in the photopic ERG. Figure 12–2 shows the d-wave in two retinas: one from the all-cone retina of the squirrel that lacks a positive-going c-wave[1, 2] and one from a monkey retina with mixed input from rods and cones that shows both c- and d-waves.[5] Intraretinal analysis of the monkey d-wave indicates that it represents a combination of the distinctive rapid offset of the cone late receptor potential (which is positive going), followed by the

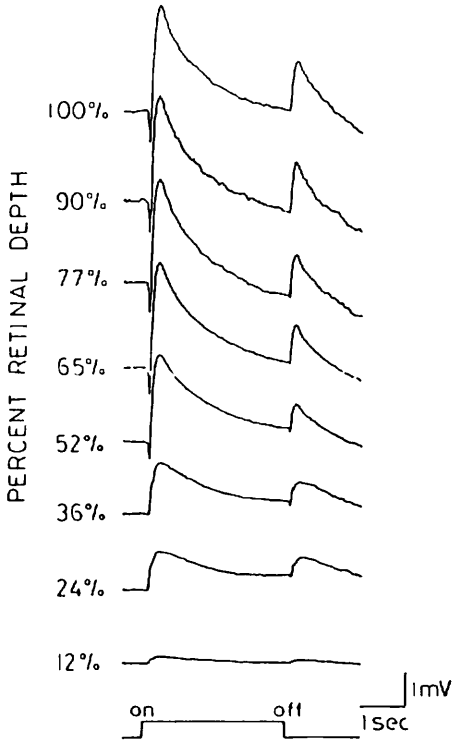

FIG 12–1.
Series of depth recordings of an ERG of isolated frog retina. The b- and d-waves are recorded at all depths, whereas the a-wave is only seen in the receptor layer and the distal part of the inner nuclear layer. The d-wave is relatively sharp at the depths where the a-wave is present, which is compatible with the off-response of the late receptor potential contributing to the d-wave. More proximally, where the d-wave is slower, the receptor contribution may be less and a Müller cell contribution more important. (From Yanagida T, Koshimizu M, Kawasaki K: *Jpn J Ophthalmol* 1986; 30: 298–305. Used by permission.)

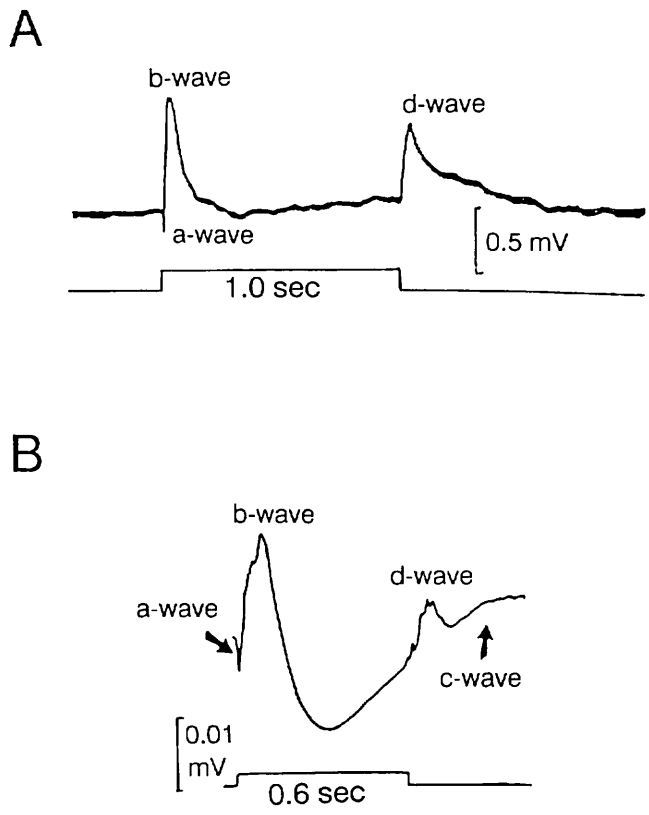

FIG 12–2.
Mammalian ERGs with d-waves. **A**, ERG from the all-cone retina of the squirrel. Recordings were made under light-adapted conditions between a contact lens electrode on the cornea and an electrode on the forehead. (From Brown KT: *Vision Res* 1968; 8:633–677 and Arden GB, Tansley K: *J Physiol* 1955; 127:592–602.) **B**, ERG of the dark-adapted cynomolgus monkey to a 640-nm pulse of light far above threshold. Recordings were made in the isolated arterially perfused cat eye preparation between electrodes that contacted the cornea and the sclera. (Adapted from Evers HU, Gouras P: *Vision Res* 1986; 26:245–254.)

negative-going offset of PII component.[2] The fast offset of the cone receptor potential was viewed clearly by using long-wavelength stimuli under photopic conditions in the monkey after clamping of the retinal circulation to isolate the photoreceptors[3, 13] and in excised human retina in the presence of aspartate.[15]

Granit[9] described a d-wave in the predominately rod ERG of the cat, but an analysis by Brown[2] indicated that it was not a true d-wave. This "d-wave" only occurred in response to the offset of very intense stimuli of long duration when the decay of the rod receptor potential, which is generally quite slow,[3, 13] was rapid enough to become visible. It appeared as a small positive deflection in the ERG that followed an initial negativity, the offset of PII. Thus, even though the offset of the rod receptor potential was quickened, it was not the initial deflection after stimulus offset, and therefore it did not form a true "d-wave."

The positive-going return of the rod receptor potential to baseline also is seen in the light-adapted ERG of cat after the negative offset of PII.[7] In contrast, in the scotopic ERG of the cat, for dim stimuli, the offset of PII is followed by a slow recovery toward baseline that is termed "remnant negativity" by Granit[8] that can be distinguished from the receptor potential. It is a slow, negative response of more proximal origin that is abolished by 2-amino-4-phosphobutyric acid (APB).[6]

In summary, the corneal d-wave in mammals (cat and monkey) is largely produced by the positive-

going offset of the late receptor potential. It is further shaped by the negative-going offset of PII. However, in mammals, unlike in cold-blooded species, to date there is little evidence for a positive-going d-wave component that originates in the proximal retina, either directly by neurons or indirectly by K^+ spatial buffering.

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