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REFRACTIONS AND REFLECTIONS

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Depth-of-Focus of the Human Eye: Theory and Clinical Implications

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Abstract. The depth-of-focus, or the perceptual tolerance of the human eye to retinal defocus, is important to and imbedded in many aspects of clinical refraction and physiological optics. Although the depth-of-focus is a common concept in classical optics, there is relatively little detailed discussion of its implications as related to normal vision function and to vision anomalies. With current advances in refractive surgery and ophthalmic lens design, the demand for knowledge in this topic is both timely and important. This review of our current understanding of the depth-of-focus should prove to be useful to clinicians, researchers, and students as an introduction to the subject. Two areas will be considered: 1) basic definitions of and factors affecting the depth-of-focus, and 2) its contemporary clinical implications. (**Surv Ophthalmol 51**:75–85, 2006. © 2006 Elsevier Inc. All rights reserved.)

Key words. accommodation • blur • depth-of-focus • lens design • optics • refraction • refractive surgery • retinocortical disease

Basic Definitions and Concepts

DEPTH-OF-FOCUS AND DEPTH-OF-FIELD

The concept of depth-of-focus is not commonly considered by many eyecare practitioners. However, it is not merely an academic topic or a subject for basic research inquiry. The depth-of-focus is used daily in the routine vision examination, as well as in the prescription of corrective lenses and most recently in refractive and lens implant surgery. The purpose of this review is twofold: 1) to overview the basic topic of depth-of-focus, and 2) to consider the clinical implications.

What do we mean by the *depth-of-focus*? It can be defined in many ways, but a simple definition is, "The variation in image distance of a lens or an optical system which can be tolerated without incurring an objectionable lack of sharpness in focus."[68] Although theoretically a perfectly clear and in-focus retinal image is present only when it is precisely optically conjugate with the retina itself, a slightly defocused image will also be interpreted in this way by the brain as long as it is positioned within the optical extent of the depth-of-focus. Thus, in essence, the depth-of-focus can be considered to provide a neurological and perceptual tolerance for relatively small focus errors. This is certainly a desirable situation that is common to all physiological feedback control systems.[35,73] Related to the depth-of-focus is the depth-of-field. It can be defined as the "projection of the dioptric interval of the depth-of-focus into free space."[53] As long as a target remains within the depth-of-field in object space, its retinal image will likewise remain within the depth-of-focus in image space, and hence clarity of the target will be perceived.

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Fig. 1 depicts the depth-of-focus and related depth-of-field of the human eye in a simple way.[18] To understand the concept of depth-of-focus better, it is important to make the critical distinction between *retinal defocus* and *blur.* Blur is a perceptual phenomenon. It is the visual sense of lack of sharpness. In contrast, retinal defocus is an optical phenomenon. It results in a reduction of the retinal-image contrast gradient.[2] Slight defocus of the retinal image will not necessarily lead to the perception of blur. It must exceed the threshold for blur perception.

Two points should be emphasized here. Firstly, when one considers the depth-of-focus and the depth-of-field, the accommodative level of the eye is assumed to be relatively fixed and not changing, except for the very small (±0.1D) and continuous oscillations of accommodation.[47] The low-frequency components may in part be involved in the sensing of blur,[87] whereas the high-frequency components probably represent a physiological pulse-related epiphenomenon.[88] One may ensure a constant level of accommodation during testing by instilling a cycloplegic agent to paralyze accommodation. Secondly, the dioptric midpoint of the depth-of-focus is theoretically situated on the retina; in other words, it is symmetrical in image space. In contrast, the depth-of-field is asymmetric relative to the conjugate point in object space, with the distal range always larger than the proximal one due to the non-linearity of diopters in object space (Fig. 1). Presence of either astigmatic errors[67] or high-order aberrations[14] would increase the depth-of-focus, with increased variability in the plane of focus.[65,74]

LAG AND LEAD OF ACCOMMODATION AND DEPTH-OF-FOCUS INTERACTION

Although the eye can be regarded as a complex optical system composed of several elements (e.g., cornea, lens, vitreous body), one can conceptualize its entire optical system to be a single, high-powered positive lens with an aperture stop. At any particular moment, and assuming that accommodation is maintained constant, only one point in object space can and will be optically conjugate with the high resolution fovea. If a target such as a Snellen letter "E" is placed at that point in object space, its image will fall precisely on the retina and will be in perfect focus. If the letter "E" is displaced either slightly closer or further from that conjugate point (Fig. 2A), the image of the letter "E" will be slightly defocused on the retina. As long as the displacement of the target is within the proximal and distal boundaries of the depth-of-field, it will still be perceived as being in focus. For example, under near viewing conditions, when one reads a newspaper at the distance of 33 cm (i.e., 3.0 D accommodative stimulus level), the accommodative response is typically less than the accommodative stimulus.[17,18] The optically conjugate point in object space is typically at a distance slightly farther than the newspaper, perhaps 38 cm (2.6 D) from the eye. Therefore, when one focuses at near, there is a lag of accommodation, with the target positioned near the proximal edge of the depth-of-focus (Fig. 2A).[34,51] In contrast, when one focuses at far, the accommodative response is typically greater than the accommodative stimulus, which is known as a lead of accommodation,[51] with the target now positioned near the distal edge of the depth-of-focus (Fig. 2B).[66] Independent of viewing distance, the eye accommodates the minimum amount to place the target within its depth-of-focus/field to see the object clearly.

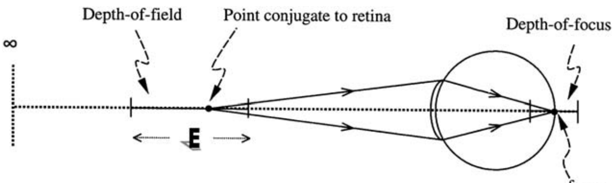

Fig. 1. Schematic depiction of the depth-of-focus and the depth-of-field. Symmetrical distal and proximal depth-of-focus components in image space versus asymmetric distal and proximal depth-of-field components in object space.

ACCOMMODATIVE STIMULUS/RESPONSE CURVE

The above points are perhaps best exemplified by inspection of the steady-state accommodative stimulus/response curve as depicted in Fig. 3.[17,18] This is one of the most important response functions to understand accommodation and its relationship to

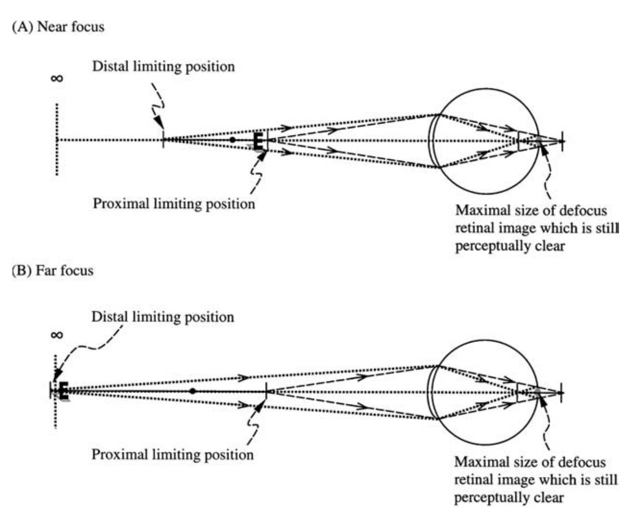

Fig. 2. *A:* Near viewing condition showing the "lag of accommodation." *B:* Distance viewing condition showing the "lead of accommodation."