Optical Characterization of Bangerter Foils

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Purpose. Optical penalization is emerging as an alternative to patching for the treatment of amblyopia. Bangerter foils offer a form of optical penalization that is distinctly different from standard techniques making use of atropine or spectacle lens manipulation, or both, to produce defocus. The authors examined the optical properties of Bangerter foils and compared them with the effect of defocus.

Methods. Bangerter foils were evaluated on an optical bench to calculate point spread and modulation transfer functions. Retinal images through the foils were also simulated and qualitatively compared with those with defocus and Gaussian blur. Subjective visual acuity and contrast sensitivity were compared in two subjects wearing spectacles with foils and with simple defocus.

Results. The optical characteristics of the Bangerter foils do not correspond well with their labeled density designation. Bangerter foils and defocus affect the modulation transfer function similarly, with more attenuation of mid-range spatial frequencies than low spatial frequencies. However, Bangerter foils do not exhibit spurious resolution and phase shifts, as does defocus.

Conclusions. The blur resulting from Bangerter filters is qualitatively different from defocus. Whether this difference is of any consequence when these two methods of optical penalization are used for amblyopia treatment remains to be investigated. (*Invest Ophthalmol Vis Sci.* 2010;51:609–613) DOI:10.1167/iovs.09-3726

Optical penalization, largely because of fewer compliance issues, has generated increasing interest as an alternative to traditional occlusion therapy for amblyopia. Optical penalization entails blurring the vision in one eye, which can be accomplished by several different means. The most widely used method is to defocus one eye by using atropine to paralyze accommodation and dilate the pupil, but manipulation of the spectacle lens prescription with or without atropine is also used.[1–4] Another approach is to apply a diffusing substance, such as translucent adhesive tape, contact paper, or a Bangerter foil, to the spectacle lens of one eye.[5–7]

Although the amount of blur can differ with each of these methods, clinicians have generally not been concerned with qualitative differences between different mechanisms of producing blur. The purpose of this study was to characterize the optical properties of Bangerter filters and to contrast the blur they produce with that produced by errors of focus and to consider whether these differences might have implications for the use of these methods for the treatment of amblyopia.

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Methods

Physical Characterization

Bangerter foils (Ryser Optik, St. Gallen, Switzerland) are available in a range (0.1–1.0) whose numerical designation is intended to represent the level to which visual acuity is reduced by the filter. We tested a set of four new, unused foils in the original packaging as labeled and shipped from the manufacturer, graded 0.8, 0.6, 0.4, and 0.3. The foils were translucent, functioning as diffusers rather than density filters. The foils were examined under direct magnification to ascertain the extent to which the microstructure of their scattering elements corresponded to their numerical density designation.

Optical Testing

The optical properties of the foils were characterized on an optical bench consisting of a He-Ne laser ($\lambda = 634$ nm) whose beam was spatially filtered, collimated, and limited to a 2-mm circular aperture. A reference point spread function (PSF) was first obtained when the collimated beam was focused in a charge-coupled device camera. PSFs for the Bangerter foils were then obtained by placing each foil within the collimated beam (Fig. 1). A Fourier transform was calculated for each PSF to obtain the modulation transfer function (MTF) for the reference condition and each Bangerter foil.

The retinal image resulting from each Bangerter foil was simulated by convolution of the PSF with a test object.[8] The test object, consisting of letters and a starburst pattern, was designed to demonstrate the effect of image degradation on optotype acuity and contrast sensitivity over a range of spatial frequencies (Fig. 2).

For comparison, simulated retinal images were also calculated using amounts of defocus and Gaussian blur adjusted to equalize the area under the radial average of the MTF with that of the Bangerter foils.

Psychophysical Testing

Visual acuity and contrast sensitivity were measured with the foils applied to the spectacles of two subjects. Contrast sensitivity was measured using an adjustment method with presentation of 12 cyc/deg sinusoidal gratings. The amount of defocus needed to produce the same decrease in visual acuity as the 0.8 and 0.4 Bangerter foils was also determined. The research followed the tenets of the Declaration of Helsinki.

Results

Magnified inspection of the foils revealed a characteristic pattern of microbubbles (Fig. 3). The number of microbubbles in the selected area of each foil can be used as an estimate of the microbubble density, which should be related to the severity of image degradation, with a higher microbubble density expected to result in a worse image. The density of bubbles (bubbles/mm^2) in the selected field was 1.5 in the 0.8 foil, 1.7

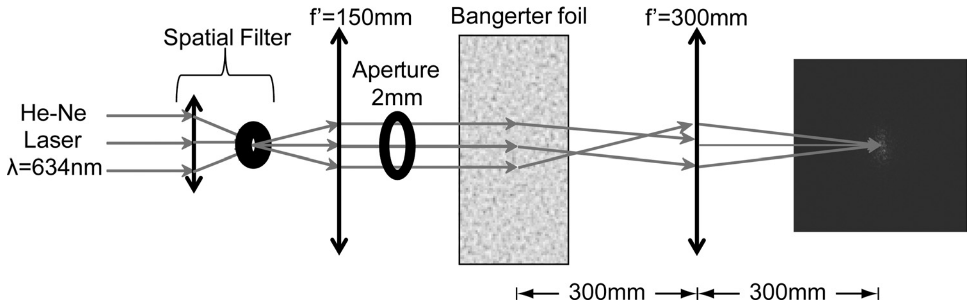

Figure 1. Arrangement of optical bench components used to test Bangerter foils.

in the 0.6 foil, 2.4 in 0.4 foil, and, paradoxically, 1.7 in the 0.3 foil.

The PSFs for the four Bangerter foils are shown in Figure 4. The radial averages of these images and the reference PSFs are shown in Figure 5, which provides a more quantitative analysis of how each foil spreads light in the retinal image. It can be seen that the 0.6, 0.4, and 0.3 foils scatter light away from the central peak to a similar degree. Only the 0.8 foil had a distinctly different effect, producing less scatter into the eccentric regions of the PSF than the other three filters.

The radially averaged MTFs (Fig. 6) show similar degradation for the 0.6, 0.4, and 0.3 foils that is more severe for high spatial frequencies. The 0.8 foil again shows less effect, but still considerably worse, than the reference MTF. Note that for a nearly symmetric PSF without negative regions in the corresponding MTF, as is the case with these filters, the phase transfer function must be nearly constant in all cases.

A relative image quality reduction parameter, which we defined as the reduction of the area under the MTF as a fraction of the area under the MTF of the reference case, shows the same hierarchy of image degradation by the different foils (Fig. 7).

Simulated retinal images of the test object with two Bangerter foils (0.8 and 0.4) are shown in Figure 8. Simulated retinal images with amounts of defocus (0.35 D and 0.6 D) and Gaussian filters that reduce the area under the MTF to the same extent as the corresponding Bangerter filter are also shown. The Bangerter foils, like Gaussian filters, produce monotonically increasing attenuation of the higher spatial frequencies. This can be observed as the contrast of the spokes at the edge of the starburst pattern progressively fades to a uniform gray near the center. Defocus also attenuates higher spatial frequencies more severely than lower spatial frequencies, but in an irregular way. This manifests itself in the central portion of the starburst pattern as bands of reversing phase (spurious resolution) separated by gray bands of zero contrast.[9,10]

The effect of each type of blur on the optotypes is also distinct. With the Bangerter filter, the optotypes become unrecognizable when the contrast becomes too low to distinguish the strokes. With defocus, it is more a distortion of the position and shape of the strokes that limits recognition.

The mean ± SE of six observations (three each for two subjects) with each Bangerter foil affixed to their spectacles is shown for visual acuity (Fig. 9) and contrast sensitivity at 12 cyc/deg (Fig. 10). The visual acuity and contrast sensitivity findings are similar, with the 0.8 foil producing the least impairment and the 0.6 foil the most; however, they show some discrepancy with the MTF data, in which the 0.4 foil gave the greatest degradation.

Amounts of defocus selected by the subjects to match the subjective appearance and visual acuity with the foils are shown in Figure 11. The visual effects of the 0.8 and 0.4 foils are roughly equivalent to defocus of 1 D and 2 D, respectively.

Figure 2. Test object for simulation of retinal images through the Bangerter foils.

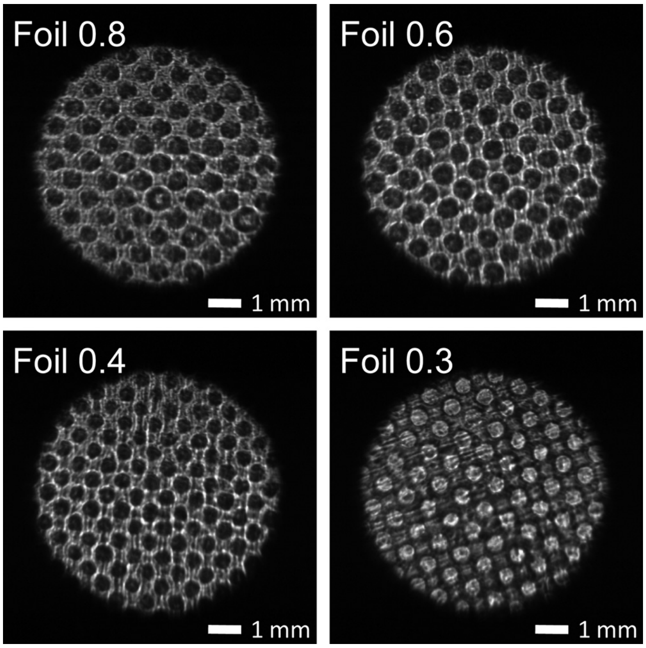

Figure 3. Photomicrographs of the patterns of microbubbles in the Bangerter foils.

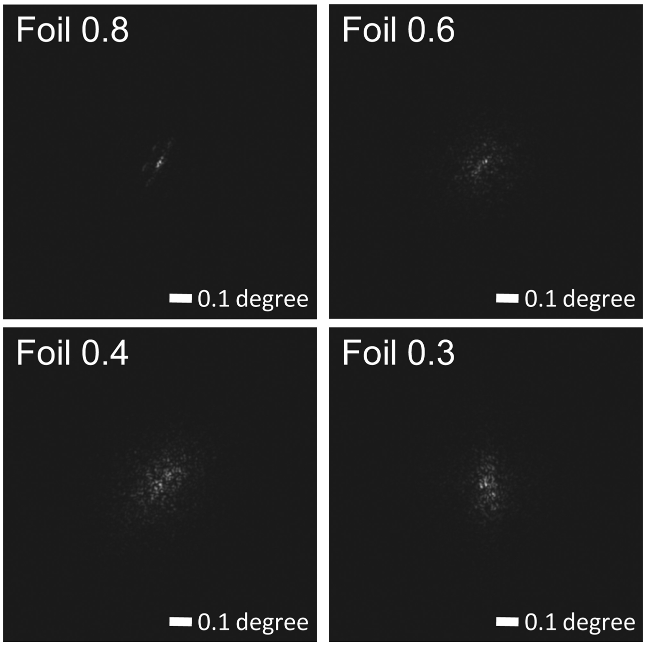

Figure 4. PSFs of the Bangerter foils.

The amount of defocus that is equivalent subjectively is greater than that which produces equivalent reduction in the area under the MTF, as used in the retinal image simulations.

Discussion

Bangerter foils come in a range of densities that are intended to provide a graded amount of blur; however, we found that both the physical structure (Fig. 3) and the optical properties (Figs. 4–7) were similar and not necessarily ordinal for our samples of the 0.3, 0.4, and 0.6 filters; only the 0.8 filter was substantially different. Odell et al.[11] also found that the amount of visual degradation did not correspond well with the density designation of the Bangerter foil.

Compared with the amount of defocus needed to produce equal areas under the MTF, substantially more defocus is needed to produce blur that is subjectively equivalent to a given Bangerter foil. Of course, this may be an artifact of using different equivalence criteria (equal MTF area vs. optotype recognition). However, another possible explanation may be that increased depth of field in real eyes due to higher order aberrations and the Stiles-Crawford effect render the effect of defocus less than what would be predicted by theoretical calculations.[12–14]

Bangerter foils are similar to a Gaussian filter in that they produce essentially monotonically decreasing contrast with increasing spatial frequency (Fig. 6). Defocus attenuates midrange spatial frequencies most severely[12]; however, though high spatial frequencies are relatively unattenuated by defocus, they are already so attenuated in the diffraction-limited case that this is not an important difference from Bangerter foils. The effects of Bangerter filters and optical defocus on the MTF are therefore grossly similar.

Spurious resolution is a potentially more important difference between defocus and Bangerter foils. The phase shifts that occur for spatial frequencies between the zero crossings in the MTF with defocus[9,10] do not occur to any substantial degree with Bangerter foils (Fig. 6). Alteration of spatial phase is thought to have an important impact on spatial perception.[15–17] Higher order aberrations and the Stiles-Crawford effect may reduce these effects, shift the zero crossings, or modify the phase shifts that occur with defocus,[12–14,18] but phase reversals with defocus are still readily demonstrated in most real human eyes.[10,19]

The effect of phase alteration is to shift image features. Examination of the blurred optotypes in Figure 8 shows some of the consequences of this. First, there is more contrast in the defocused images because the phase shift causes adjacent black or white areas of the object to superimpose at some

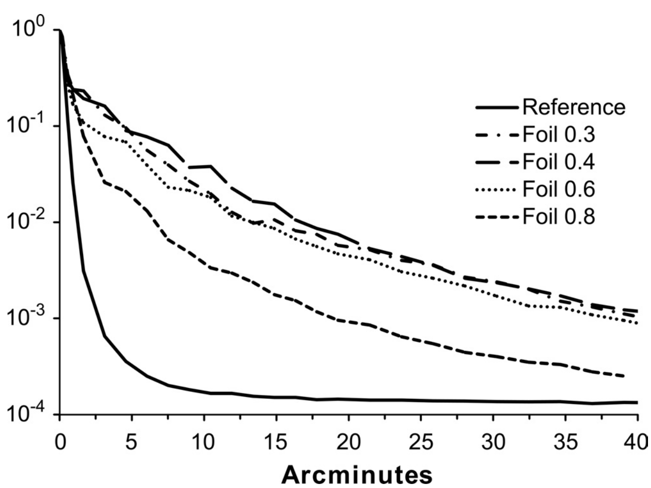

Figure 5. Radial average of the Bangerter foil and reference PSFs.

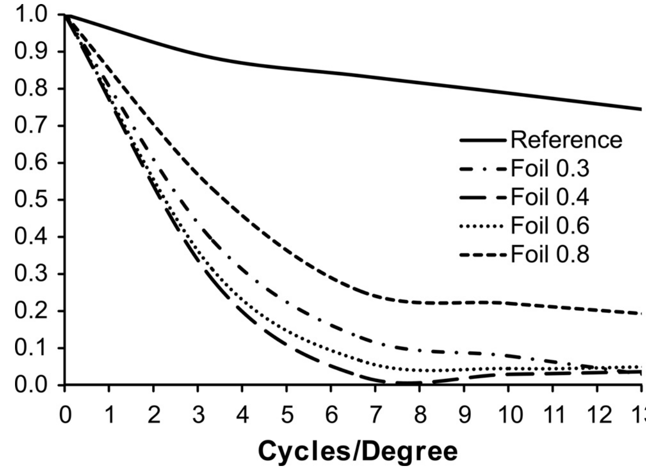

Figure 6. Radial average of the Bangerter foil and reference MTFs.

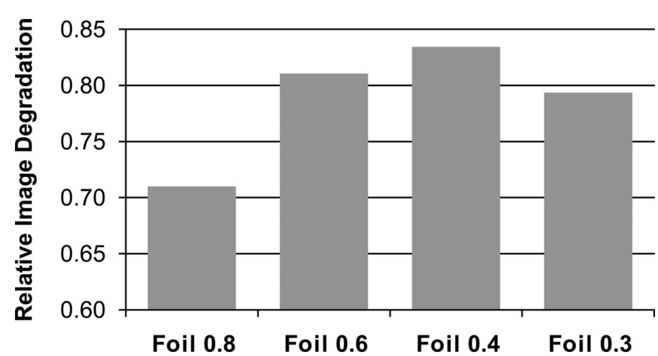

Figure 7. Image degradation resulting from each Bangerter foil as a fraction of the area under the reference MTF.

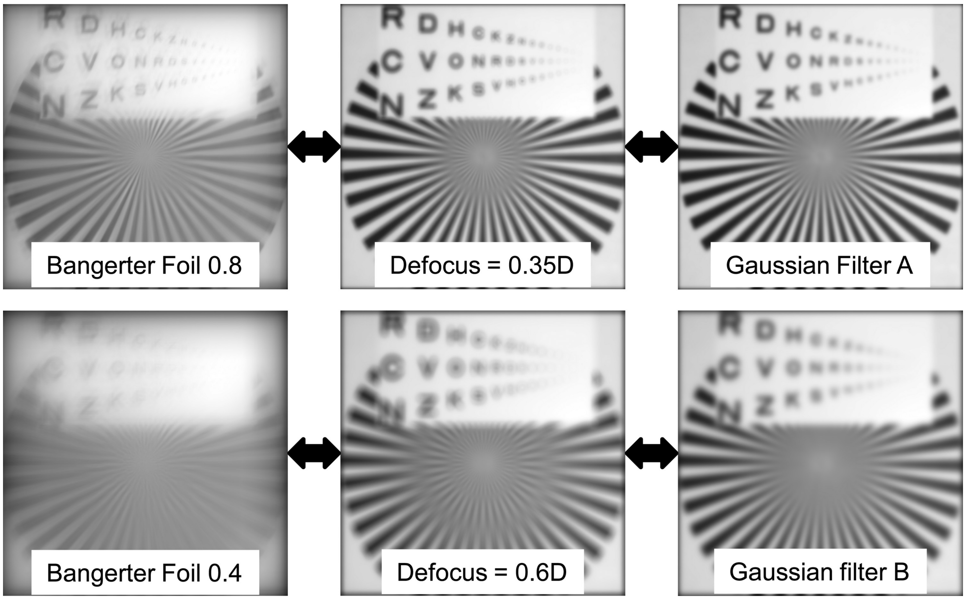

FIGURE 8. Simulated retinal images through 0.8 and 0.4 Bangerter foils compared with defocus and Gaussian filters with the same area under the radial average of the MTF.

points in the image. Even with considerable defocus, there are still areas of the image that are quite dark and quite bright, whereas the images through a Bangerter filter tend toward a more uniform gray. Second, though an optotype stroke in the Bangerter filter image may be considerably spread out, the true location of the stroke is always in the center (which is also the darkest point) of the area over which its image is spread. With defocus, however, the elements of the stroke can be shifted, with the darkest points sometimes occurring at an edge or in a different location altogether (see, for example, the "S" in the 0.35 D frame or the "O" in the 0.6 D frame of Fig. 8).

Compared with Bangerter foils, the spatial uncertainty introduced by defocus may have a distinct interaction with amblyopia, in which a defect of spatial localization[20–22] or phase perception[23] has been proposed as a component of the visual deficit. Treatment of amblyopia by optical penalization involves degrading the vision in the sound eye; however, it is unclear what aspects of vision are most important. Moreover, Bangerter foils and defocus may affect these aspects of vision differently. For example, defocus will allow the penalized eye to experience higher contrast than a Bangerter foil. If specific spatial frequency channels are important, the spurious resolution that occurs with defocus will lead to less consistent suppression of these channels than will occur with a Bangerter filter.

A theoretical advantage of optical penalization is that it permits binocular vision and stereopsis, which is not possible during occlusion therapy. However, phase shift may cause differences in the degree to which defocus and Bangerter filters disrupt stereopsis. For example, Westheimer and McKee[24] found that monocular defocus caused a loss of stereoacuity that was disproportionate to the loss of visual acuity, whereas Bangerter filters appear to produce proportional degradation of visual acuity and stereoacuity.[25,26] Stereoacuity may

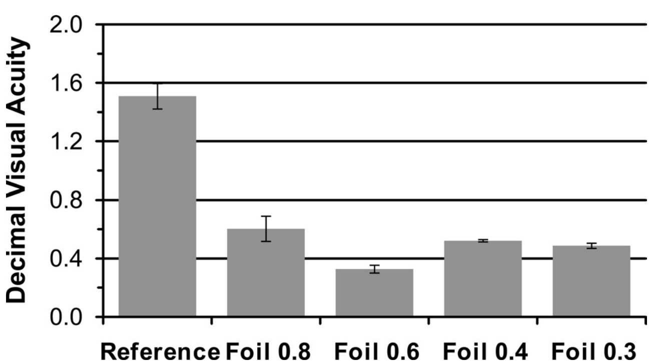

FIGURE 9. Decimal visual acuity with Bangerter foil affixed to spectacle lens.

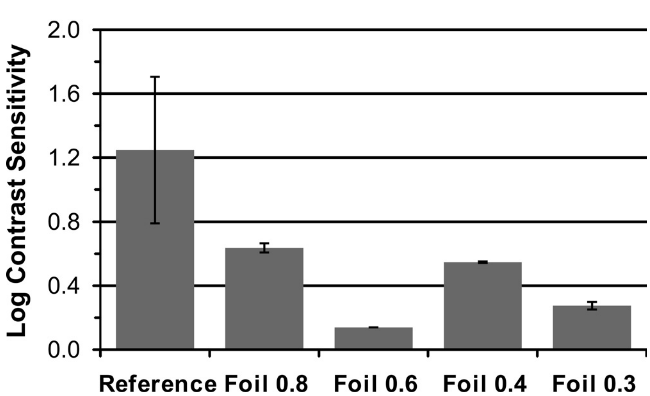

FIGURE 10. Log contrast sensitivity at 12 cyc/deg with Bangerter foil affixed to spectacle lens.

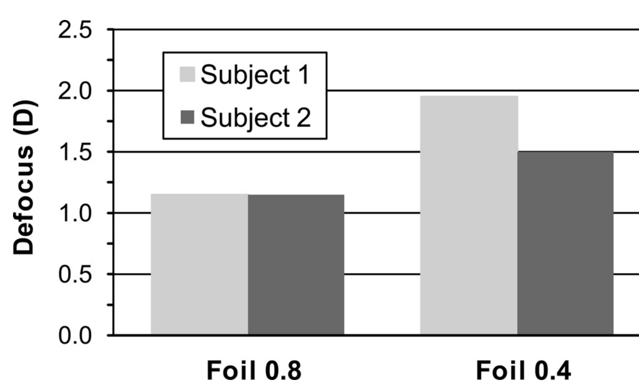

FIGURE 11. Amount of defocus selected by each subject to produce visual acuity comparable to 0.8 and 0.4 Bangerter foils.

be affected minimally or not at all when Bangerter foils are used in amblyopia treatment.[7]

Because Bangerter filters produce blur that is qualitatively different from defocus, there may not be equivalent "doses" that produce identical results. Whether this difference is of any consequence when these two methods of optical penalization are used for amblyopia treatment remains to be investigated.

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