Correction of chromatic aberrations in GRIN endoscopes

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A gradient-index (GRIN) endoscope can be constructed by substituting for the usual objective and relay sections suitable cylindrical index-distribution rod lenses. Currently available GRIN lenses exhibit large amounts of chromatic aberration. Axial color arises mostly from the relay lens, while lateral color is due to the objective lens. A negative lens cemented to a shortened GRIN relay lens can simultaneously correct axial and lateral chromatic aberrations with commercially available components. This correction system reduces the requirements for mechanical centration better than do color correctors that are incorporated into the ocular design. Monochromatic aberrations are also considered.

I. Introduction

An endoscope is an optical device for visualization in body cavities; examination of the internal anatomy through a puncture wound represents the least traumatic means for direct visualization. Depending on the application, the endoscope can be configured as an arthroscope, gastroscope, laparoscope, or cystoscope, among others. For joint surgery of the knee, a 4-mm o.d. rigid arthroscope is typically used. A conventional endoscope contains of the order of fifty spherical surfaces. For smaller joints, a thinner arthroscope is preferred. Because of the difficulty in manufacturing classical lenses with diameters of the order of 1 mm, gradient-index (GRIN) optical components with planar faces are employed.

Currently available GRIN optics exhibit large amounts of chromatic aberrations, severely degrading resolution. Previous attempts at reducing the chromatic aberrations have focused on overcorrecting the ocular. Because of the large amount of lateral chromatic aberration, centration tolerances between the needle portion of the endoscope and the ocular become difficult to meet. A corrector lens system consisting of a plano-concave lens cemented to the back of the needle portion reduces the problem of mechanical centration between the ocular and the relay system better than do color correctors that are incorporated into the ocular design.[1]

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II. Optical Train of Uncorrected System

Figure 1 is a schematic of a typical gradient-index endoscope.[2] The gradient-index elements have a quadratic cylindrical index distribution and are 1 mm in diameter. The space created by the 2.2-mm o.d. is filled with an annular optical fiber bundle for illumination. The ocular consists of a doublet microscope objective coupled to a Ramsden eyepiece. Figure 2 shows the optical train of the needle portion in greater detail. An object, nominally 3 mm from the front face of the endoscope, is imaged by the GRIN objective lens onto its rear face. In use, the depth of field is sufficient to satisfactorily focus between 1 mm and infinity. A cover glass protects the GRIN objective from the environment. The high numerical aperture objective increases the field of view of the endoscope. The GRIN relay lens then serves to transfer the image the required penetration depth. The relay lens may be cut to any integral number of half-periods to form an image on its rear face. The period of a GRIN relay is the length required for a ray to trace a complete sine wave. A standard relay length is two periods, or 134 mm, as shown. The orientation of the image may need to be reversed in the ocular when there are an odd number of half-periods in the relay to present an upright image to the eye. Finally, a rear cover glass is cemented to the back of the relay lens, again for environmental protection. The aperture stop of a gradient-index endoscope is the wall of the relay lens, one-quarter period out of phase with the internal images.

The performance of a commercial gradient-index endoscope, the Needlescope,[3] which uses Selfoc[4] gradient-index lenses, is very nearly diffraction-limited in monochromatic light. The theoretical limit of the resolution in d light is ~200 lines/field or ~16 μm at an object distance of 3 mm. The resolution in white light is half of this value because of chromatic aberrations. Axial chromatic aberration in a two-period endoscope

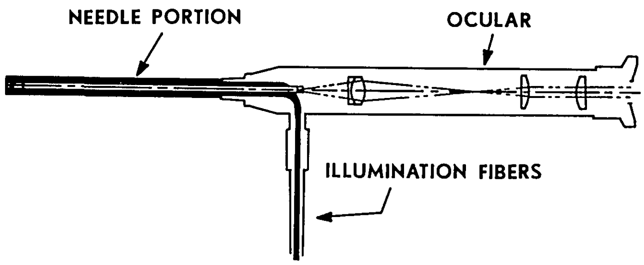

Fig. 1. Typical gradient-index endoscope. The needle portion consists of GRIN optics. The ocular is a compound microscope.

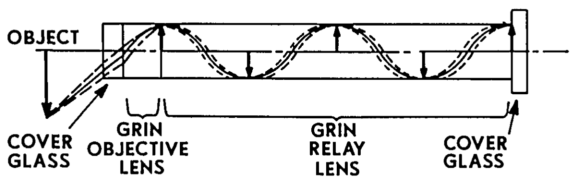

Fig. 2. Optical train of needle portion. The object is imaged onto the rear face of the objective lens and reimaged the required penetration depth to the back of the relay lens.

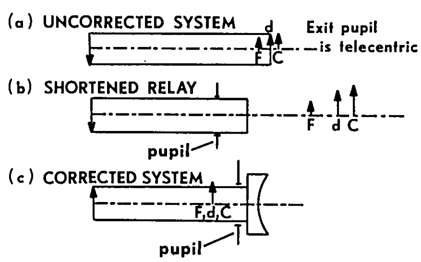

Fig. 3. Relay lens of gradient-index endoscope showing chromatic aberration correction procedure.

is ~0.8 mm, with the greatest contribution due to the GRIN relay lens. Of course, the longer the relay lens, the greater the axial color will be. The lateral chromatic aberration or chromatic variation of magnification is due solely to the GRIN objective; because of symmetry, the relay lens cannot contribute to lateral color. Currently manufactured scopes are undercorrect in both axial and lateral color as shown in Fig. 3(a).

III. Correction Procedure

The exit pupil of an uncorrected needle section is telecentric. To correct the undercorrect lateral chromatic aberration with a negative lens, the pupil must be to the left of the image. This can be accomplished by shortening the relay by an amount less than a quarter period. This projects the image into the air space behind the relay lens and creates an exit pupil inside the relay lens [Fig. 3(b)]. As the relay length is reduced, the image and the exit pupil move to the right. It should be mentioned that the loss of symmetry introduces a lateral color contribution from the relay lens. When the relay length is reduced by a quarter period, the image is at infinity and the pupil is at the rear face of the relay lens. At a relay lens reduction of less than a quarter period, with a negative lens fixed onto the end of the relay, a virtual image can be formed inside the relay, with the exit pupil also inside the relay but closer to the rear face. This configuration acts to correct the axial and lateral chromatic aberrations. By choosing the correct combination of relay lens length and corrector lens curvature, the axial and lateral chromatic aberrations can be eliminated completely [Fig. 3(c)].

The correction procedure is straightforward. The curvature (c) required to correct axial color is easily calculated from paraxial optics as[5]:

$$C = \frac{1}{l_d} + \frac{N_d}{N_F - N_C} \frac{l_C - l_F}{l_d^2}, \tag{1}$$

where $l_{d,F,C}$ = image distance in corrector lens material, and $N_{d,F,C}$ = refractive index. To reduce the required curvature, a glass with small n/dn is chosen. Several glasses, including Hoya AOT-5, Schott SF-57, and Kodak EK812, are satisfactory.

Figure 4 is a plot of lateral color vs relay lens length when the curvature is chosen according to Eq. (1). Because the image size after the needle portion varies widely with different relay lengths, we found it convenient to normalize aberrations to the Rayleigh tolerance. A constant overall magnification is maintained by the ocular design. A base relay lens length of 1.5 periods was chosen so that an erect image can be viewed through a compound microscope ocular. It can be seen that a relay length of 88.4 mm eliminates both axial and lateral color using the Hoya glass. The radius of curvature required is ~4.5 mm.

As an aside, it should be mentioned that, although we have designed a corrector for a gradient-index endoscope with both undercorrect axial and lateral color, correctors for other combinations of chromatic aberrations can be envisioned (Fig. 5). For currently available GRIN materials, a shortened relay with a negative lens is required as discussed above. Overcorrect axial color requires a positive lens, while overcorrect lateral color requires a relay length longer than an integral number of half-periods.

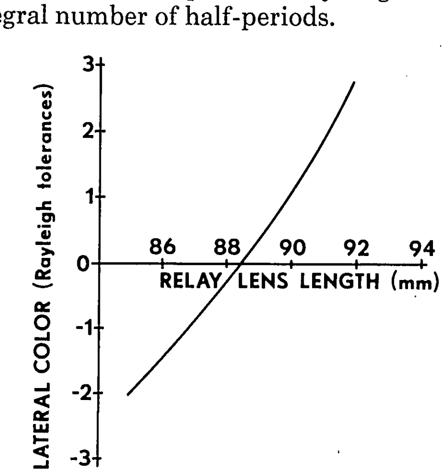

Fig. 4. Lateral chromatic aberration vs relay length with zero axial color; AOT-5 glass.

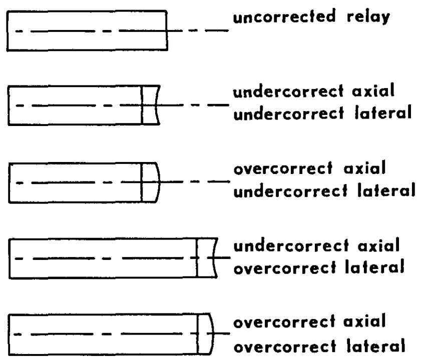

Fig. 5. Alternate correction configurations. Commercially available GRIN optics are undercorrect in both axial and lateral color.

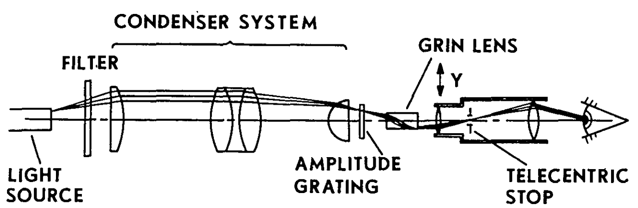

Fig. 6. Schematic of arrangement for the measurement of distortion.

IV. Monochromatic Aberrations

No mention has been made of the monochromatic aberrations caused by shortening the GRIN relay lens and adding a corrector. The loss of symmetry of the relay introduces coma, astigmatism, and distortion in addition to lateral color. To better evaluate the monochromatic performance of the gradient-index endoscope, a third-order optical analysis was performed.[6,7] It should be mentioned that the GRIN objectives lens operates at a half-field angle of ~25°, so a third-order analysis must be used cautiously.

To calculate the third-order aberrations, the fourth-degree index coefficient h_4 must be known. Since h_4 is a sensitive parameter of third-order distortion, a measurement of distortion can be compared with the third-order aberration to estimate h_4. To measure distortion, the setup of Fig. 6 was constructed. A light source filtered for d light illuminates a sinusoidally modulated linear amplitude grating. The grating is imaged onto the back of the GRIN objective lens, which is, in turn, viewed with a microscope. The telecentric stop defines the chief ray of the system. It is then a simple matter to measure the positions of the grating fringes as the microscope is swept across the field.

The third-order distortion can be computed from a polynomial expansion of the fringe positions. If the microscope displacement (y) as a function of fringe number (n) is fitted to the form

$$y(n) = a_0 + a_1(n - n_c) + a_2(n - n_c)^2 + a_3(n - n_c)^3 + \dots, \qquad (2)$$

the third-order distortion (D) is

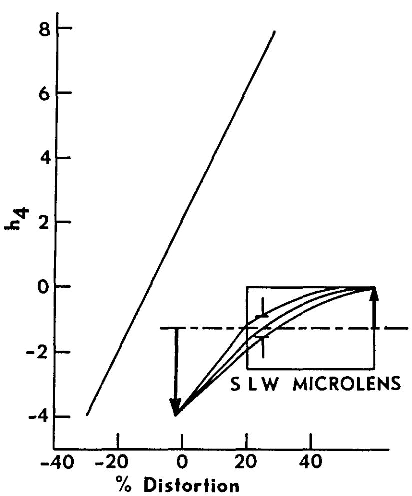

Fig. 7. Third-order distortion of Selfoc objective lens vs h_4. Object distance is adjusted for zero image distance.

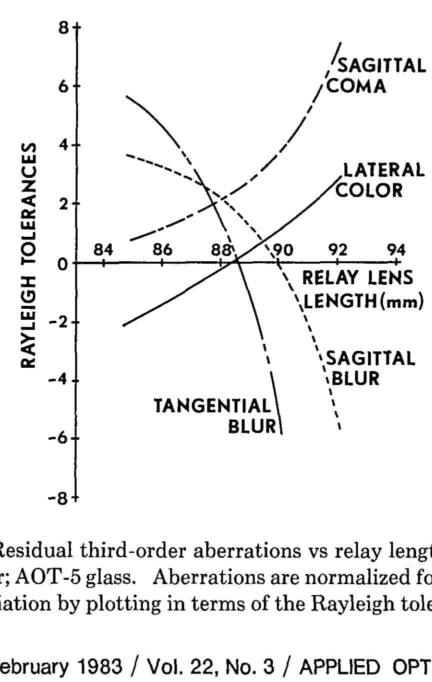

Fig. 8. Residual third-order aberrations vs relay length with zero axial color; AOT-5 glass. Aberrations are normalized for image size variation by plotting in terms of the Rayleigh tolerance.

Table I. Specifications of Color-Corrected Endoscope

Surface	Curvature	Thickness	Glass
0	0.0000	3.4073	air
1	0.0000	−0.3164	air
2	0.0000	3.0000	GRIN objective
3	0.0000	16.8150	GRIN relay
4	0.0000	70.1850	GRIN relay
5	0.0000	1.0000	AOT-5
6	0.1942	−5.7402	air
7	0.0000	4.1376	air
8	0.0000	5.7200	air
9	0.0000	0.8300	F-5
10	0.3000	1.9000	BK-7
11	−0.2330	68.9052	air
12	0.0000	12.4335	air
13	0.0000	2.0000	BK-7
14	−0.0390	26.1000	air
15	0.0390	2.0000	BK-7
16	0.0000	−500.0109	air
Object half-field	0.482		
Invariant	−0.0356		
Image height	−38.2 mm		
Magnification	23.3		
Exit pupil distance	26.0 mm		
Exit pupil height	−0.490 mm		
Transverse spherical	114.5 μm	(0.05 Rayleigh tolerance)	
Sagittal coma	−277 μm	(0.94 Rayleigh tolerance)	
Sagittal blur	−819 μm	(2.8 Rayleigh tolerances)	
Tangential blur	−795 μm	(2.7 Rayleigh tolerances)	
Distortion	−16.6%		
Transverse axial color	−2.63 diopters	(1.15 Rayleigh tolerances)	
Lateral color	69.5 μm	(0.12 Rayleigh tolerance)	

$$D = \frac{a_3}{a_1}(n - n_c)^2_{\max} * 100\%, \tag{3}$$

where n_c is chosen to minimize the even-order polynomial terms.

To estimate the third-order distortion as a function of h_4, paraxial ray traces were done on the axial and chief rays, and calculations were performed to determine the surface and transfer contributions, which are a function of h_4. Figure 7 is a plot of h_4 as a function of the calculated third-order distortion for the conjugates shown. Several Selfoc objective lenses were measured, yielding an h_4 of approximately −1.5. The third-order aberrations of a gradient-index endoscope are not sensitive to the h_4 of the GRIN relay lens.

Figure 8 plots the relevant third-order aberrations as functions of the relay lens length when the corrector lens curvature is chosen to correct axial color. The aberrations are normalized by plotting in terms of Rayleigh tolerances, one Rayleigh tolerance corresponding to a maximum ray fan optical path error of a quarter-wavelength. Distortion is a relatively innocuous aberration in endoscopes, and quite large values are usual. Curvature of field is also well tolerated and is easily accommodated by the eye in visual instruments. Of the remaining aberrations, it can be seen that the presence of coma pushes the optimum relay lens length to a shorter value than is required when considering only the chromatic aberrations.

V. Discussion and Conclusions

A prototype endoscope was designed for zero chromatic aberration and constructed using EK812 as the corrector material. As expected, no measurable color was evident. However, coma at the edge of the field was objectionable. By using the Hoya glass with its smaller n/dn, the residual coma was made smaller. The monochromatic aberrations can be further reduced to an acceptable level if the corrector lens is designed to fully correct only lateral color, leaving some axial color for correction in the ocular. This reduces the surface contributions from the curved surface of the corrector lens, while retaining the decentration insensitivity. The specifications for the final design are shown in Table I.

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