THE INDUCTION OF REFRACTIVE ERRORS BY RETINAL DETACHMENT SURGERY*

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INTRODUCTION

AS THE MODERN THERAPY OF RETINAL DETACHMENT HAS EVOLVED, ALONG WITH the increased likelihood of surgical success and its attendent improvement in the visual result, the consequences of the surgical procedure itself on the induction of refractive error has risen in importance. Müller[1] in 1903, with his introduction of the scleral resection (full-thickness) procedure, hypothesized the generation of a considerable amount of residual hypermetropia following his operation. During the past 15 years, this has been confirmed repeatedly (Borley,[2] Frey,[3] Shapland,[4] and Rosenthal[5]), the hyperopia being more transient when the scleral resection is lamellar or segmental and more permanent when accompanied by an encircling element (a polyethylene tube in the cases reported above). More recently, (Grupposo,[6] and Jacklin[7]), the striking tendency is for the induced refractive error to be towards myopia (or less hyperopia) in contrast to the hyperopia found earlier. In addition, both regular and irregular astigmatic changes induced by various external and internal buckles have also been reported periodically (Givner,[8] Grupposo,[6] Rosenthal,[5] Wolter,[9] Fiore,[10] Jacklin,[7] Burton,[11] and Mensher[12]).

It is the purpose of this report to examine the type and amount of refractive error induced by the encircling operation for the repair of retinal detachment through a clinical study of 1,477 eyes that had detachment surgery, to explore (through additional clinical and laboratory studies) the parameters influencing the optical errors induced, and to analyze the optics which seems to explain the clinical findings. As far as we can determine, such an analysis has not been reported to date.

The initial portion of the report deals with a retrospective clinical study of refractive error in patients with retinal detachment. While we are in full agreement with Norton's[13] reservations and emphasis of the drawbacks of the typical retrospective study of retinal detachment repair,

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we feel ours is somewhat less subject to "retrospective bias" than one involving a large number of subjective clinical judgments. Our particular effort has yielded results which have proved to be quite valid statistically; it has led us to certain conclusions about the refractive error induced, despite the fact the basic data were retrospectively determined. After the discovery of the basic points regarding the extent of the refractive changes, we designed prospective laboratory and analytical evaluations which are also discussed in this paper.

RETROSPECTIVE CLINICAL STUDY

METHODS

During the past 12 years, we have performed scleral buckling operations for retinal detachment in 3,905 eyes, of which 3,573 (92% overall) were successfully repaired. The primary surgery as well as any secondary surgery was performed at one hospital. Of these, 1,477 eyes described in this report fulfilled the following criteria:

1. The eye underwent successful anatomical repair of the retinal detachment with a minimum follow-up time of one year.
2. An external "encircling" procedure was performed with a #40 silicone silastic band.
3. Mention had to have been made in the record of the subjective judgment of the "height" of the intraocular indentation created by the encircling band. (It is customary for us to evaluate and remark on this point).
4. Only "external" buckling procedures were included. These might have utilized, in addition to the encircling band, explants of 3, 5, or 7 mm sponge or a #20 grooved silastic explant. That is, any of these explants might have supplemented the encircling band, but not necessarily. No eyes with scleral resections were included.
5. Only cryotherapy was utilized to create the chorioretinal adhesion; no eye with diathermy treatment is included.
6. The patient's record must have indicated the preoperative refractive error. This was most often given in the form of previous corrective spectacles. This refraction forms the "baseline" error for each patient in this study.
7. At least one postoperative refraction (or retinoscopy, if the best acuity was not better than 20/200) must have been performed no earlier than two months postoperatively. In a series of patients on whom repeated refractions were done later than two months following the surgery, aside from some astigmatic reductions,

there was no significant, further basic refractive error change, and this led to the selection of a two-month time interval for "cutoff".

The most common reason for eliminating a particular patient with retinal detachment from this study was simply because he did not have an encircling procedure performed; that is, he required only segmental, localized explants. Also, prior to 1966, scleral resections (and diathermy treatment) may have been used; these examples are not reported in this study.

Therefore, the 1,477 eyes comprise a series of consecutive, successful silastic encircling procedures (with or without accessory silastic explants) with preoperative and postoperative refraction data.

Supplemental data were obtained in a prospective manner in some of the last 250 patients who fulfilled the above criteria. Keratometry readings were made in 75 of these patients and pachometer readings of the anterior chamber depth were made in 26. A-scan and B-scan ultrasonograms for axial measurements were also obtained in at least 20 patients, but the repeatability and measurement reliability were quite unsatisfactory for our purposes and so these data were deleted.

DISCUSSION

In this paper, we do not elaborate on the many factors concerning or influencing our retinal detachments, that is, their history, vitreous status, number and position of tears, probable duration, the extent of the detachment, complications, and so forth. Our findings are very comparable to those presented in other, well documented reports (Bagley,[14] Norton,[13] Schepens,[15] Smolin,[16] and Ashrafzadeh[17]). Although this paper is not designed to report on the surgical and visual results obtained in our series of 3,905 patients, a few pertinent comments about those results are not out of place, since these do help orient the reader to our general approach.

Of the total number of procedures performed, 3,593 (92%) experienced an "anatomical cure" lasting at least one year following the final surgical procedure. For aphakic detachment, the rate is about 90%; for phakic detachment, it is about 93%. After 1966, when we shifted to the exclusive use of cryopexy and external buckling procedures for detachment repair, our anatomical results continued to be quite comparable vis-à-vis our earlier procedures using diathermy and lamellar scleral resections with implant buckling. Of interest, however, is a significant general improvement in terms of visual results since 1966, despite the fact that a greater number of more difficult detachment problems have been seen since that time. We would like to think these improved visual results can be attributed to our general philosophy in the care of patients with retinal detachment which is certainly not novel but does seem to work. Simply, it is to do as little as possible to repair the detachment. We emphasize the use of relatively small quantities of explant material with a minimal number of sutures to hold the "hardware" against the sclera without risking explant movement (Rubin and Fitzgerald[18]). Other tenets of our approach are the creating of as little distortion of the globe as necessary, tightening the explant sutures only minimally, avoiding unnecessary drainage, and using only minimal to moderate (in contrast to heavy) cryotherapy* which is applied only to the obviously diseased vitro-retinal patch.

How important any of these specific factors are depends, of course, on the particular requirements of each particular patient. It is fair to say that applying a philosophy which stresses moderation in therapy has enabled us to provide what we feel is probably "state of the art" anatomic repair of retinal detachments. As mentioned, the visual results have actually improved. Of those who preoperatively had their macular areas already detached, 41% attained 20/50 or better acuity one year postoperatively (with even greater improvement at two years), whereas in a comparable group prior to 1966, only 28% achieved this level of performance.

RESULTS

Of the detachments referred to our University, there is a significantly higher percentage of aphakic detachments (41%) than is reported elsewhere (Schepens[19] 23%, Norton[13] 33%). This is probably indicative of the older population groups in our vicinity as well as the greater likelihood for patients with retinal detachment who are aphakic to be referred to a university. Our state has a high incidence of retired people. There is also a propensity for our patients to have had their cataracts extracted in the North and then develop their detachments while winter-vacationing in the South. To help support this hypothesis, Table I is presented and indicates that the number of eyes in this series as well as the proportion of aphakic detachments was higher in the December through May semi-annual period than in the comparble June through November period (819 to 658, and 43% to 38% respectively).

*Despite laboratory evidence that heavier cryotherapy provides a stronger chorioretinal adhesion, we feel that even minimal cryotherapy "burns" provide an adhesion which is sufficiently strong to form a clinically useful, tenacious adhesion.

TABLE I: FREQUENCY OF DETACHMENTS RELATED TO SEMI-ANNUAL PERIOD

	December through May		June through November		Total	
	Number	%	Number	%	Number	%
Phakic	464	57	408	62	872	59
Aphakic	355	43	250	38	605	41
Total	819	100	658	100	1,477	100

The unusually high percentage of aphakic patients in this selected group of detachments reported in Table I might well be an artifact related to the fact that we included only those patients having encircling procedures. Since the eyes of patients with aphakic detachments are more likely to be encircled than are those of phakic patients, any incidence figures based only on those encircled would necessarily show a bias towards aphakia. In fact, one might anticipate that this factor alone would account for the entire difference in the incidence of aphakia between our group and other series. Such a possibility was amenable to testing. We compared the ratio of aphakic to phakic eyes (shown in Table I) to that found in our entire detachment population of 3,573 eyes without regard to whether or not an encircling procedure was done. Surprisingly, however, the aphakic percentage still comprised about 38% (compared to 41% in the encircled series). Comparable percentage figures for each of the half-year data shown in Table I were also found to be reasonably representative of our entire detachment population. Thus, in this series, there is no essential difference in the ratio of aphakic/phakic eyes between those encircled and those without regard to encirclement.

Needless to say, this finding surprised us. Since we know that our current practice is an almost universal encirclement of those eyes with aphakic detachment, we fully expected the aphakic percentage in the encircled population to have been much higher than that in the entire detachment population. So, how do we reconcile our anticipated result with the actual result?. As follows: Table I presents data covering a 10-year period. In the early part of that interval, we were using encircling elements in aphakic eyes less frequently than we do at present, and for phakic eyes, more frequently than now. When we restudied the data and considered only the final 3 years of this 10-year series, we confirmed what we suspected — the incidence distortion created by our current management (encircling almost all aphakes) yielded 58% aphakia among the encircled eyes. This incidence figure now fits our expectations more closely!

TABLE II: FREQUENCY DISTRIBUTION OF DETACHMENTS (BY AGE OF PATIENTS)

	Phakic		Aphakic	
Age	Number	% of Total	Number	% of Total
0-20⁻	29	2	15	1
20-40⁻	44	3	28	2
40-60⁻	473	32	178	12
60-80⁻	282	19	325	22
80 over	44	3	59	4
Totals	872	59	605	41
Mean Age	55.6		66.9	

Table II shows the frequency distribution by age of the 1,477 patients in this study. The mean age of the phakic patients was 55.6 years and that of the aphakic group, 66.9 years — similar to other studies. Though these data refer to only those detachments in this reported series (that is, with encircling bands and successful results) this mean age is not significantly different from that found when we recalculated the mean after including all 3,905 of our retinal detachments, which include all failures as well as all successful reattachments utilizing explants alone.

Moving on to the primary purpose of this study, Tables IIIA and IIIB indicate the frequency distribution of the preoperative refractive errors in phakic and the aphakic eyes, respectively. Our study does not exclude traumatic detachments and does include every retinal detachment that fulfills the criteria established originally. Since our selection criteria for this study are different from those of other authors who may have used different categories and end-points (Ashrafzadeh and associates,[17] Cambiaggi,[20] or Schepens and Marden[15]) we cannot fairly compare our refractive errors with theirs. For example, in Ashrafzadeh's recent series, a refractive correction of − 1 D or more was taken to indicate "myopia". However, to indicate an aphakic eye which was basically myopic, he assumed the aphakic "equivalent" of a correction − 1 D was + 10 D. However, at the aphakic spectacle lens plane (the common reference position for any refractive spectacles) the correction which corresponds to − 1 D is closer to + 9.3 D. Thus Ashrafzadeh's choice of a + 10 D dividing line would necessarily cause him to include a larger number of aphakic "myopes" than if he used + 9.3 D as the "break-point." We used + 9 D as the myopic cutoff. So, one might anticipate that we would have found a lower percentage; instead we found a still higher total percentage (33%—from Table IIIB; 15% + 12% + 6% = 33%). However, Ashrafzadeh's series includes only aphakic patients over age 38.

We used no such age cutoff; our figures include 43 (15 + 28) aphakic eyes* under age 40 (see Table II) and include patients having had congenital or traumatic cataracts as well as "senile" cataracts. These types of variations in patient selection or data cutoff exemplify the lack of complete comparability of data among various reports.

TABLE IIIA: FREQUENCY DISTRIBUTION OF BASIC (PRE-OP) REFRACTIVE ERROR (SPHERICAL EQUIVALENT)

	Phakic	
Error (Diopters)	Number	%
Over +3	43	5
+3 to $+1^+$	123	14
+1 to −1	314	36
−1 to -1^-	159	18
−5 to -3^-	87	10
−7 to -5^-	78	9
Over −7	68	8
Total	872	100
Mean	−1.91 D	
S D	1.87	

TABLE IIIB: FREQUENCY DISTRIBUTION OF BASIC (PRE-OP) REFRACTIVE ERROR (SPHERICAL EQUIVALENT)

	Aphakic	
Error (Diopters)	Number	%
Over +13	40	7
+13 to $+11^+$	128	21
+11 to $+9^+$	235	39
+9 to $+7^+$	93	15
+7 to $+5^+$	73	12
+5 or less	36	6
Total	605	100
Mean	+8.34 D	
S D	1.52	

From Tables IIIA and IIIB, the mean refractive error in the phakic group was − 1.91 D (S D = 1.87) with a definite skewing towards myopia, while the mean refractive error in the aphakic group was + 8.34 D (SD = 1.52), which as pointed out above, is also on the "myopic" side. Because our distributions of refractive errors reflect our particular referral population as well as our selection criteria, it is all the more remarkable how closely

*Of interest is that 80% of these 43 young eyes were "myopic" if we consider an error of less than + 9.3 D postoperatively as evidence of myopia.

most reported distributions correspond. The data shown in Tables IIIA and IIIB are not basically different from those of other studies, which agree remarkably as to the marked tendency of patients with retinal detachment to be myopic.

It should be kept in mind that this study was not conducted to determine anything about the general incidence of refractive error in the population of retinal detachment patients, nor was any effort made to exclude any specific type of retinal problem. The consideration here was simply to determine the amount of refractive error change induced by an encircling element; to that end, Tables IV through VI were prepared.

TABLE IV: FREQUENCY DISTRIBUTION OF CHANGE IN REFRACTIVE ERROR

	Phakic		Aphakic	
	Number	%	Number	%
$+1.00^{+}$ to $+2.00$	13	1.5	16	3
Plano^{+} to $+1.00$	44	5	34	6
-1.00^{+} to plano	146	17	376	62
-2.00^{+} to -1.00	553	63	148	24
-3.00^{+} to -2.00	106	12	26	4
-4.00^{+} to -3.00	10	1.1	5	1
Total	872		605	
Mean change in refractive correction (spherical equivalent)	-1.70 D		-0.91 D	
S D	0.67 D		0.58	

Table IV provides a tabulation showing one of the basic results of our correlative analysis. This table relates the frequency distribution of the change in refractive error in both phakic and aphakic eyes following the encircling procedure for detachment repair, that is, the change from the preoperative to the postoperative status, determined at least two months following surgery. Because many of the patients had some superimposed astigmatism (both preoperatively and postoperatively), we used only the spherical equivalent for the comparisons shown. On the other hand, we did determine the amount of astigmatic change, though this is not shown here. In this latter analysis, 11% of these eyes exhibited an increase of over ½ diopter in their astigmatic correction. This change was not considered to be significant. However, 3% had more than 1 diopter (most were related to anteriorly placed explants) and a few had even more marked astigmatic inductions. These are discussed later in the section on "Corneal Curvature."

Table IV also shows that the mean change in the refractive error in the phakic eye was − 1.70 D (SD = 0.67 D) and in the aphakic eye, − 0.91 D (SD = 0.58 D). Statistically these prove to be very significant differences confirmed by a t-test which yields a calculated t-value of 24.127 on 1,475 degrees of freedom. This gives a p-value of less than .0001.

This analysis establishes with virtual certainty that we have two distinct population groups, phakia and aphakia, specifically in regards to the relative ability of an encircling band to induce a refractive error.

TABLE V: MEAN CHANGE IN REFRACTIVE ERROR (SPHERICAL EQUIVALENT) RELATIVE TO HEIGHT OF INDENTATION

	Phakic				Aphakic			
Height of Indentation	No.	%	Mean Change	S D	No.	%	Mean Change	S D
Low	463	53	−1.56	.33	284	47	−0.74	.40
Moderate	357	41	−2.24	.72	266	44	−1.41	.69
High	52	6	+0.35	.94	55	9	+0.59	.89
Total	872	100	−1.70	.67	605	100	−0.91	.58

Table V reveals the most significant and novel clinical findings of this overall study. Two factors are compared: the change in refractive error (spherical equivalent) between the preoperative and postoperative state and the indentation height created by the encircling band (as judged subjectively by this observer).

This examiner's subjective impression as to the height of the indentation of the band (that is, whether it was "high," "moderate," or "low") is based on a routine comment pertaining to this parameter noted on each patient's chart sometime during his postoperative course. The height of this indentation does not seem to be related to the length of time after surgery; if it is "moderate" one month postoperatively, it almost assuredly remains "moderate" one year later.

This judgment of the height in this retrospective study is the only factor that is truly subjective and thus subject to observer bias. Thus, it is especially important to stress that the reason this parameter was originally evaluated was not with a view towards obtaining possible refractive error correlations, but simply to determine whether the height of the band's indentation increases the tendency for intrusion of that band into the globe, such as is occasionally noted with the previously used polyethylene tubes.* In other words, this examiner's estimation of the height of the

*Only one such intrusion has occurred at our institution with silastic. This occurred in a patient with a very thin, previously diathermized sclera under a small section of the encircling band.

band indentation was not likely to have been biased towards any specific refractive error change, since, at the same time such judgments were initiated, no study of this type was being considered.

It would have been better if we had had an objective means to measure the height of such indentation. A priori reasoning might lead one to assume a good correlation with the amount (length) of band "cinched up" at surgery. However, such is not necessarily the case. Five years ago we used to measure, as advocated by Lincoff, the length of band pulled up prior to anchoring the ends. However, within a few months, we ceased this practice as we found it unnecessary and no more reliable than our clinical judgment about how far to pull up the band; the primary factors being the extent of vitreous traction, the ocular pressure (that is, whether or not drainage of subretinal fluid was necessary), and to what extent post-drainage retinal wrinkling had occurred.

In any case, postoperatively, *subjective* clinical judgment of the final height of indentation is indeed quite repeatable when subdivided into only three categories. These three subdivisions, though somewhat arbitrary, are not difficult to distinguish from one another. Other physicians who are experienced in examining retinas agree rather strikingly in any given judgment of this height. A judgment of "low" (via indirect ophthalmoscopy and with a + 20 or + 30 D viewing lens) indicates that there is definite visibility of the band's pressure effect, but that effect is "just visible" either by retinal pressure signs ("white-with-pressure"[21]) or by stereoscopic value. "Moderate" signifies that there is a distinct posterior edge to the band's "push", yet the retina is fully visible on the posterior slope created by the band. A rating of "high" signifies the indentation is indeed significant; the posterior slope of the retina is so steep that it is hidden from direct view.

When the retina overlying the indentation is viewed with a direct ophthalmoscope and compared to the flattened retina just posterior to the band, we found that "high" always indicated at least 5 D of internal elevation.

Sometimes the band's indentation is uneven over the equatorial circumference; that is, it may be higher in some areas than in others. This could be due to variation in scleral thickness, or if one or two of the mattress sutures which anchor the band are placed too tightly, they can "hang up" the band creating the uneven pressure. So, in each of these three categories, a specific label is given only if at least ⅔ of the circumference is indented to the extent of the rating.

It is clear that the category of "high" encompasses a much greater range of indentations than either of the other two. The band's push can be "high" or "very high", yet it is still recorded as "high". Even so, (from Table V) only 6% of phakic detachment repairs and 9% of aphakic repairs resulted in a "high" circumferential indentation. (This emphasizes our striving for minimalization of surgical interference).

As might be surmised from the data, we tend to use the encircling silastic #40 band frequently — approximately 75% of the time. However, recall that we have a high proportion of aphakic and other, more extensive and complicated detachment problems referred to us; many are not "typical" or "average." In our locale, the umcomplicated retinal detachments are very likely to be treated routinely by "non-retinal center" ophthalmologists, and thus, the simpler problems are selected out. Although there is a need to encircle a higher proportion of our patients, the encircling band is tightened only sparingly; this is shown in Table V which indicates the preponderence (51% overall) of "low" band indentations.

But more importantly, Table V indicates in summary form, that with encircling procedures, there is a general tendency for the refractive error to increase in a myopic direction as the band height is increased from "low" to "moderate." This induced error is greater in the phakic than in the aphakic eye. This was pointed out by Jacklin[7] in a series of 25 patients; it is confirmed in the present series of 1,477 patients and, in addition, is correlated with the height of indentation. Table V shows that when a "high" indentation is produced, the means of the dioptric refractive shift have changed decidedly towards hyperopia! Statistical evidence is very strong (at better than the 1% level of confidence) that these findings are indeed real, that is, the tendency for this peculiar refractive error change, is highly significant. The primary question this generates is, "How can one account for this unexpected change?"

We attempted to determine whether the preoperative refractive error itself influences the extent of the error changes induced by the indentation. Tables VIA and VIB (for the phakic and aphakic states respectively) show the mean refractive error changes induced by "low," "moderate," and "high" band indentations. These data are also subdivided into three degrees of preoperative refractive error: hyperopia, basically emmetropia, and myopia, for both phakic and aphakic eyes. These tables indicate that there is essentially no difference in the mean refractive error change related to the preoperative refractive error. The significant changes are related only to the different heights of band indentations as already mentioned.

Neither Jacklin[7] nor any other reference sources we can locate attempt to explain the discrepancy between the error induction in phakic versus aphackic patients. We also have not found any other study pointing out

TABLE VIA: MEAN REFRACTIVE ERROR CHANGE (DIOPTERS) IN 872 PHAKIC ENCIRCLING PROCEDURES COMPARED TO THE PREOPERATIVE REFRACTION AND BAND INDENTATION HEIGHT

Preoperative refraction	% of eyes	Band Indentation: Low (53%)	Moderate (41%)	High (6%)	Mean (calculated by preoperative ref. error)	
More than 1 D hyperopia	(19%)	−1.42	−1.96	−0.22	−1.57	
1 D hyperopia to 1 D myopia	(36%)	−1.60	−2.41	+0.40	−1.81	Overall Mean
More than 1 D myopia	(45%)	−1.52	−2.15	+0.10	−1.68	−1.70
Mean (calculated by extent of band indentation)		−1.56	−2.24	+0.35		

TABLE VIB: MEAN REFRACTIVE ERROR CHANGE (DIOPTERS) IN 605 APHAKIC ENCIRCLING PROCEDURES COMPARED TO PREOPERATIVE REFRACTION AND BAND INDENTATION HEIGHT

Preoperative refraction	% of eyes	Band Indentation: Low (47%)	Moderate (44%)	High (9%)	Mean (calculated by preoperative ref. error)	
More than 11 D hyperopic	(28%)	−0.71	−1.50	+0.57	−0.94	Overall
11 D to 9 D hyperopic	(39%)	−0.64	−1.45	+0.50	−0.89	Mean
Less than 9 D hyperopic	(33%)	−0.79	−1.30	+0.62	−0.88	−0.91
Mean (calculated by extent of band indentation)		−0.74	−1.41	+0.59		

the correlations shown here between the induced refractive error shift and the height in the band's indentation. The attempt to explain this relationship as well as the investigation of the "paradoxical" shift occurring with high indentations will form the basis for the balance of this paper.

After discovering the correlation between the refractive error changes and the "height" of the indentation, we needed some additional information to complement this study. These empirically, analytically, and prospectively determined details help elucidate some interesting and pertinent clinical information and will be subdivided into the following topics: corneal curvature, axial length, and lens position shift.

CORNEAL CURVATURE

Does the encircling silastic band, as it compresses the equatorial region of the globe, secondarily influence the corneal curvature (by increasing it) and thus account, at least in part, for the general shift toward myopia occurring after retinal detachment repair? To answer this question, we performed corneal curvature measurements with a keratometer (Bausch and Lomb) in 75 consecutive patients with equatorial encircled retinal detachments. Initially, we attempted to refine our determinations by using a Soper-Sampson-Girard Topogometer[22] attachment; however, we soon abandoned the use of this accessory as we found, contrary to our expectations, it complicated the collection of data and did not add easily interpretable figures to the data we were gathering. Thus we relied on the standard keratometer and measured the power of the central corneal "cap" for this aspect of the investigation.

RESULTS

Analyses were made of the preoperative and postoperative keratometry readings by the individual's major meridional power changes, by group means, and by the spherical equivalent shift in the corneal powers. Though not all the data will be shown, the essential findings are demonstrated in the following tables. The repeatability or "reading error" in the performance of keratometry was 0.31 D.

TABLE VIIA: PREOPERATIVE CORNEAL CURVATURE (IN DIOPTERS)

	Phakic (42 Patients)		Aphakic (33 Patients)	
Major Meridian Power	Mean	S D	Mean	S D
Minimum	43.12	1.83	44.11	1.95
Maximum	43.88	1.79	45.98	2.03

TABLE VIIB: POSTOPERATIVE CORNEAL CURVATURE (IN DIOPTERS)

	Phakic (40 Patients)		Aphakic (31 Patients)	
Major Meridian Power	Mean	S D	Mean	S D
Minimum	43.28	1.84	44.15	1.99
Maximum	43.93	1.78	45.83	2.05

Tables VIIA and VIIB (paired tables) are each subdivided into phakia and aphakia and show the preoperative and postoperative group means of the minimum and maximum meridional corneal powers as well as the standard deviations of these values. Statistical calculations confirm what is apparent in the tables, that is, there is no statistically significant power difference generated by the encircling procedure.

Note that Table VIIB (the postoperative group) shows four fewer patients. Although these four did not show any generalized change in corneal power, they did show obvious localized keratometric corneal distortion, which will be explained below.

The preceding tables show only group means, which could have masked

TABLE VIII: THE FREQUENCY DISTRIBUTION (NUMBER OF PATIENTS) OF THE PREOPERATIVE VERSUS POSTOPERATIVE CORNEAL POWER CHANGES

Power Change D	Phakic (40 Patients)			Aphakic (31 Patients)		
	Major Meridian		Spherical Equivalent	Major Meridian		Spherical Equivalent
	Minimum	Maximum		Minimum	Maximum	
−1.12 to −0.76	1	1	0	1	2	1
−0.75 to −0.38	4	3	3	3	4	2
−0.37 to 0	13	13	15	7	9	8
0 to +0.37	10	11	18	9	9	14
+0.38 to +0.75	8	9	4	8	5	4
+0.76 to +1.12	3	2	1	2	1	2
+1.13 to +1.50	1	1	0	1	1	0
Mean	+0.16 D	+0.05 D	−0.10 D	+0.04 D	+0.15 D	+0.20 D
S D	.31	.33	.19	.42	.39	.24

significant individual changes. Table VIII was constructed to show the frequency distribution of the specific corneal power changes calculated for individuals* by major power meridian and by spherical equivalent change, along with the appropriate means and standard deviations. Each of these results has also been analyzed and again confirms that there is no statistically significant corneal power change produced by the band. Some individuals did show some corneal power changes (both spherical and astigmatic) which may have been clinically significant for them. Other data groupings (not shown), especially one which includes "band indentation height", similarly proved that there was no consistent induced power change. While a priori reasoning might lead one to suspect that a very high equatorial indentation would distort or increase the corneal curvature, clinically we found that this did not occur.

DISCUSSION

The results of this study, based on the keratometer readings, were statistically unequivocal for all groups of patients. With low, medium, and high band indentations and for both phakic and aphakic detachments with equatorial bands, there was no significant, consistent change in corneal curvature which could be related to the silastic band encircle-

*Refer to Table VIII: a given individual might have had the power in one of his major corneal meridians changed by + 1.00 D and the power in the other meridian changed by only + 0.25 D. His data would be tabulated in one row for the change in his minimum meridian, another row for the change of his maximum meridian, and still a third for his spherical equivalent change (+ 0.62 D). Thus, the horizontal rows in the table enumerate changes in the individual parameters noted which may or may not represent values obtained in individual eyes.

ment. This reported data accounts for 71 (95%) of the 75 patients in this aspect of the study.

However, as noted, four patients (5%) did have a distortion of the cornea. In each of these eyes, concomitant with encirclement, an anteriorly placed explant was also used to repair the detachment — a sponge, a grooved implant, or a very anteriorly placed band whose position came as far forward as the ora serrata (especially nasally). Only then was distortion noticeable in the keratometer readings. We emphasize that we feel such distortion was not due to encirclement per se, but to the anterior explants and sutures.

We have noted such distortion before and after this study. It is most often created by a sponge which is positioned merdionally, very anteriorly, and sutured as close as 7 mm from the limbus. In these eyes, the highest curvature power readings tend to be found in the same corneal meridian as that of the long axis of the sponge. Such refractive axis information is not very useful clinically since the astigmatism induced is irregular and cannot be corrected with spectacle lenses; it can, however, occasionally be improved, but not eliminated, with hard contact lenses. Even with very anterior buckles, surprisingly, we have found that only occasionally is any clinically significant corneal "wrinkling" produced, though in one case we found approximately 10 diopters of irregular astigmatism. When the cornea is so distorted, accurate keratometric measurements are difficult to obtain because of the twisted and flattened reflection mires. Fortunately, most of this distortion error tends to decrease (though not to zero) within six months time. This experience seems similar to that reported by other retinal surgeons (Burton,[11] Mensher[12]).

In this present series, the four examples occurred as we were beginning to use explant sponges. Actually, only one of the anteriorly placed sponges required removal — not because of infection, but only because of the patient's visual symptoms. As in Burton's report, these visual complaints responded dramatically to the restoration of the patient's normal corneal curvature following the sponge removal. The detachment did not recur.

At the present time, the frequency of induced distortion by such anterior sponges is very low. We find our incidence of visual complaints as well as general postoperative symptomatology has definitely been reduced since we stopped using full-thickness explant sponges and substituted partial thickness sponge segments to create the "buckle" (as described at the 1972 meeting of the Gonin Retina Club in Miami).

Notwithstanding the occasional (5%) objective corneal distortion and irregular power change we found to be created by the anteriorly placed buckles, we reiterate that our "standard" band encirclement procedure did not cause a recognizable change of the average patients' mean corneal power. After we analyzed our data and arrived at this conclusion, we stopped taking routine preoperative corneal power measurements and used keratometry only postoperatively in the occasional instance when the patient complained of "distorted vision." Incidentally, the majority (though not all) of such symptomatic patients do not have keratometric distortions visible. They also, typically, have undistorted retinoscopic reflexes. Thus the symptoms in these individuals are most likely due to retinal distortion (wrinkling, irregular settling, or preretinal membrane formation) following detachment surgery rather than to optical causes.

Our finding that encirclement does not tend to induce corneal curvature change is at variance with a study of over 200 scleral bucklings by Mensher and Burton.[12] Their data do indeed point to significant corneal curvature changes following surgery for retinal detachment in their average patient. However, they did not limit their presentation to strictly encircling procedures as we did, nor did they attempt to correlate the induced corneal changes they found with the quantitative "extent" of their surgical intervention, or to the positional placement or "height" of their buckles. Moreover, many of their patients had scleral resection with flaps as well as large implants or full sponge or solid explants. In contrast, our report emphasizes our efforts towards a minimal surgical intervention, aside from our more frequent use of an encircling element. We have stressed our use of very small explants and partial thickness sponges and, more importantly, in none of our patients was a scleral resection performed. A comparison between ours and the Mensher-Burton study only emphasizes our contention that corneal power change is not encountered unless one uses very anterior buckles or (what appears to be) relatively extensive scleral surgery, in which case extreme corneal curvature irregularity can well occur. In other words, we do not feel that our findings really conflict with theirs. This supports the idea that more "hardware" and more extensive surgical procedures are likely to produce more induced corneal distortion.

Wiedenthal's comment[23] also indirectly stresses that minimal retinal detachment surgery (via externally applied sponges, though creating a "permanent buckle") does not influence refractive error and hence is unlikely to influence the general corneal curvature.

In summary of this aspect of the present report, the standard encircling procedure itself does not change the corneal curvature; thus, the induction of clinically manifest refractive error by the circumferential band is clearly not accomplished through any significant influence by it on the corneal power.

AXIAL LENGTH

Concurrent with the clinical studies on corneal curvature, we investigated if and how variation in the axial length of an eye was mechanically induced by the encirclement. In addition, we attempted to learn how any change which did occur would in turn influence the amount and kind of induced refractive error.

To study these, we undertook a set of simple laboratory and optical analyses. We began with an *in vitro* examination of the effect of the height of the encircling indentation on the axial length of the eye.

LABORATORY EVALUATIONS

Using eyebank eyes in a series of ten experiments, we sutured a #40 silicone band circumferentially about the globe, with 4 to 8 mattress sutures of 5-0 Dacron, 12½ mm from the limbus in one set of five eyes, and pre-equatorially (10.5 mm from the limbus) in another set of five eyes. By calipers with a vernier scale, we measured (with a reading error of ± 0.1 mm) the vertical dimension equatorially (from the outside surfaces of the encircling band) and the outside axial length (from the central cornea to the posterior pole) and noted how these dimensions changed at various stages of band constriction.

This procedure required our monitoring the intraocular pressure with a Mackay-Marg electronic tonometer. Attempt was made to maintain the intraocular pressure at approximately 20 mm Hg.

Initially, these soft, eyebank eyes required an infusion of saline (via a 30 gauge needle placed through the optic nerve) to bring the pressure up to 20 mm Hg, but later, as the band was tightened, the release of intravitreal fluid (via the same route) was necessary to keep the eye's intraocular pressure from rising as the encircling band was adjusted.

TABLE IX: INFLUENCE OF ENCIRLING BAND ON THE SHAPE OF AN ENUCLEATED HUMAN EYE
(MEAN MEASUREMENTS OF 10 EYES)

Indentation By Band	Axial Dimension		Vertical Dimension	
	Mean	S D	Mean	S D
None	23.95	.17	25.20	.18
Low	24.39	.21	24.73	.19
Moderate	25.04	.20	24.27	.18
High	23.60	.19	23.10	.21

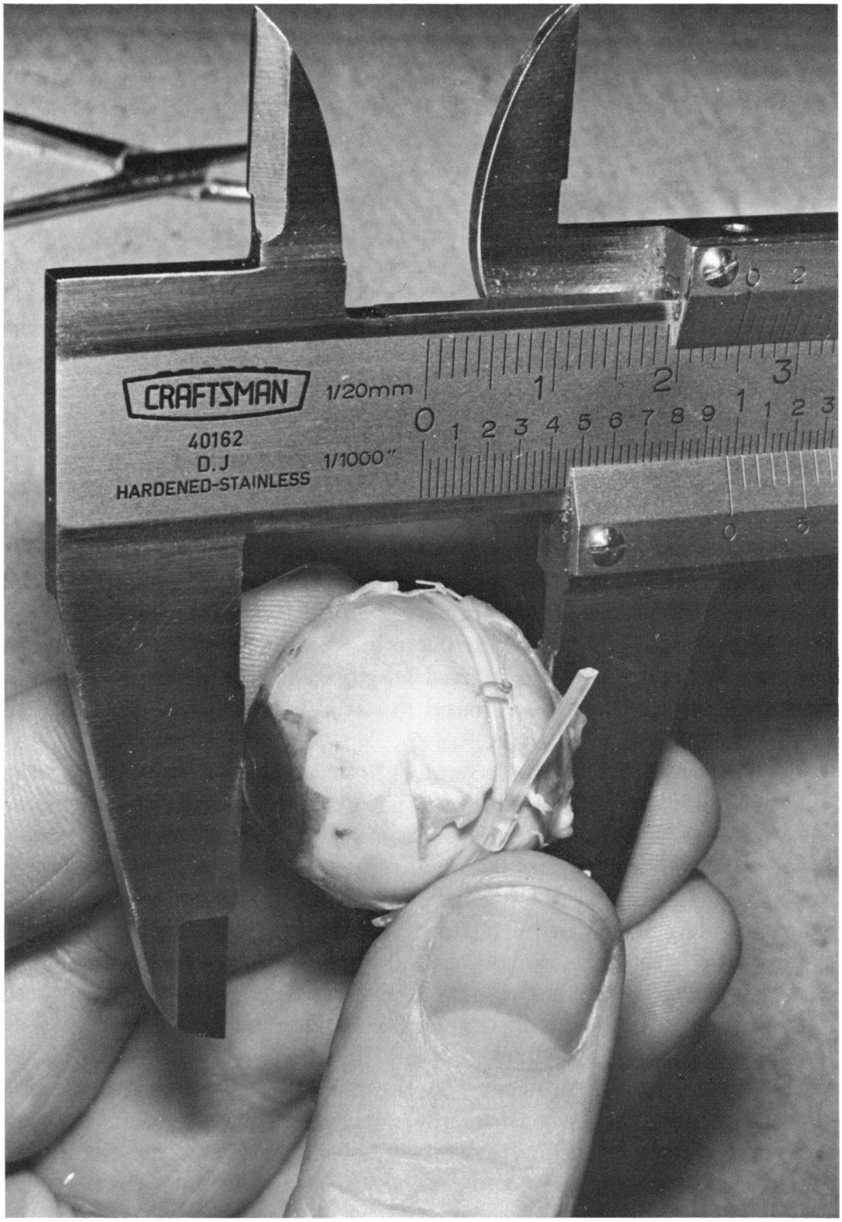

FIGURE 1
This photograph shows an eyebank eye with an encircling band tightened enough to generate what we have called a "moderate" indentation.

We compiled the data for the five eyes with equatorial and the five with pre-equatorial bands. After finding there was no significant difference between these groups in the axial length effects created by tightening the circumferential band, we combined the laboratory data in Table IX, which show the mean measurements obtained in the ten eyes. This table also indicates our subjective consideration of "low," "moderate," and "high" indentation effects by the band. Here, however, the judgment is made on the external appearance of the indentation. This is probably only loosely correlated with the clinically-judged internal indentations used in the retrospective clinical study. Though we had hoped we could actually correlate these indentations in the laboratory, the media in the eyebank eyes were too cloudy to allow visualization of the internal band height so we had to limit ourselves to the external judgment.

Figure 1 shows an eyebank eye with an encircling band tightened enough to generate what we have called "moderate" indentation.

The actual measurements of the vertical dimensions as they correlate with the sujectively determined indentation categories are shown in Table IX along with the axial length dimensions. Though the reading accuracy was ± 0.1 mm, the table includes the hundredths figure generated when the means and standard deviations are calculated. In all instances the standard deviations were about 0.2 mm. Since we were dealing with human eyes some variation in axial length was anticipated. It is rather remarkable how constant we found the axial length to be — at least in these ten eyes.

In an effort to increase the accuracy, both A-scan and B-scan ultrasonic measurements on the eyebank eyes were attempted.* However these were found to be unsatisfactory. We quickly abandoned the electronic gadgetry in favor of the manual measurements with the calipers. Though not extremely accurate, it is certainly ample for these determinations.

For the demonstration purposes we intended, the data presented here are sufficiently accurate to make the following points: *in vitro* experiments with a "low" to "moderate" indentation by an encircling band (and with the pressure maintained at 20 mm Hg) show that the axial length gradually increases somewhat (23.95 to 25.04 or 1.09 mm) over that existing prior to the encirclement. However, as the band is tightened to provide a "high" indentation, the axial length stops increasing and definitely decreases. We did not attempt to determine that specific vertical indentation measurement which seemed to reverse the direction of the axial length

*The B-scan unit we used was our clinical Bronson-Turner Ophthalmic B-scan manufactured by Grumman Health Systems. The A-Scan unit was a Smith-Kline Ecoline.

change, but it is somewhere between the "moderate" and "high" readings (see Table IX) at an intraocular pressure of 20 mm Hg.

A surprising phenomenon (which would be difficult to show in a table) becomes apparent in the instance of "high" indentation, though it also occurs to a lesser extent with the other indentations. Table IX indicates that with a "high" indentation, the mean axial length at an intraocular pressure of 20 mm is 23.60 mm. However, if the intraocular pressure is then reduced to a level of say, 10 mm Hg, the axial length shortens visibly and measurably; that is, concomitant with the intraocular pressure reduction, the tightened band creating the "high push" is no longer counterbalanced by the intraocular pressure. At the lowered pressure, its stretch and tension relaxes; its inherent elasticity causes it to constrict further, which in turn causes the axial length to shorten further. With the intraocular pressure at 10, the mean axial length is reduced to 21.07 mm. This difference of 2.53 mm additional shortening could create a very significant influence on the refractive error induction — about 7 D in a hyperopic direction! This pressure-mediated effect, then, may add to the axial shortening created by the "high" indentation which occurs even at a pressure of 20 mm Hg. The extent of the anterior-posterior shortening which finally takes place with "high" indentations, thus depends on the steady-state intraocular pressure, which provides the counterpressure to the band's tension.

In summary of this aspect of the report, this laboratory demonstration shows that as an equatorial band is tightened, it will not create a gradually increasing amount of axial lengthening. It only does so initially; further constriction reverses the change in axial length.

SCHEMATIC ANALYSIS

We now wished to confirm the foregoing eyebank eye experiments by a schematic analysis. Though we certainly do not claim this to be a profound study, it does provide a fair, though approximate, model for the effect of a constricting equatorial band on axial length (anterior-posterior diameter) of the eye. Similar analyses performed in the past tended to examine only the volumetric changes and effects on the vitreous rather than the effects on the axial length (Urrets-Zavalía[24]).

If one were to attempt a true mechano-mathematical analysis, it would be critical to know the exact scleral thickness in close proximity to and at the band position, how that thickness varies throughout the entire sclera, the "rigidity" or elasticity of the sclera, the factors influencing scleral rheology, the resistance created by the attached choroid and the other intraocular layers, as well as the effect on all these by the intraocular pressure. All such factors and their interplay would have to be taken into

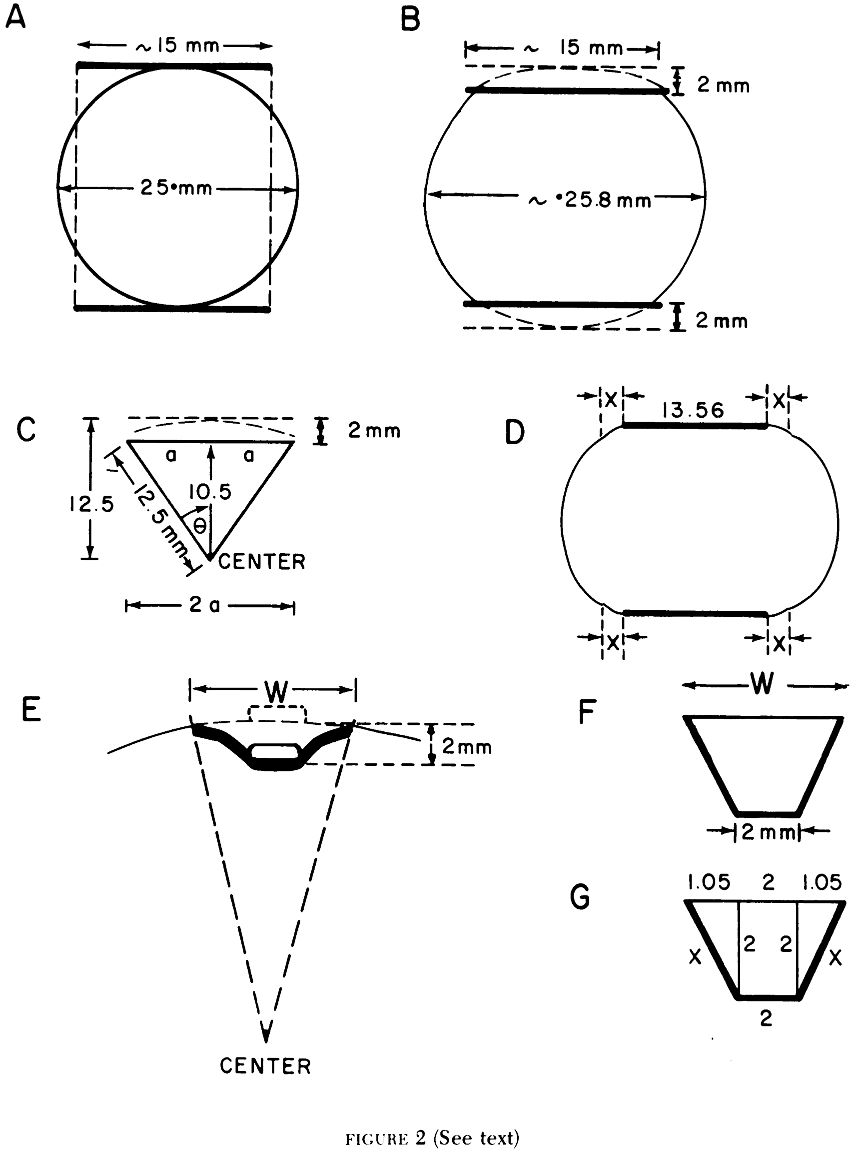

FIGURE 2 (See text)

consideration for a comprehensive evaluation. However, our point here is not to derive an exact mathematical formulation, but to demonstrate diagramatically, using approximate mathematical simplifications to describe what happens as a band is tightened.

Let us first assume the eyeball is a perfect sphere with a pliable, thin but inelastic surface covering. This covering is to be the rough analogue for sclera. If the circumferential band were stiff and 15 mm wide, then equatorial constriction of a spherical globe by the band would result in a cylindrical flattening to the inside dimension of the band. Though the internal volume of the sphere would be obligatorily reduced as the band was constricted, the perimeter (in the plane section diagrammed in Figure 2) would not change by this constriction if the sphere's internal pressure could be released as the band was tightened. Thus, as this band constricts from position A in the figure to position B, the axial diameter (axial length) must increase. The amount of such an increase is determined as follows (consult Figure 2):

If one radius (12.5 mm long) of this sphere is indented a distance of 2 mm inward (as shown in B and C*) the length from the sphere's center to the chord shown is now 10.5 mm and the chord length, $2a$, would be calculated as follows:

$$a^2 + 10.5^2 = (12.5)^2$$

$$a^2 = 156.25 - 110.25$$

$$a^2 = 46$$

$$a = 6.78 \text{ mm}$$

Chord length $2a = 2\ (6.78) = 13.56$ mm

The original arc length (subtended by the chord)

$= 2\ \Theta$ (radians) $\times$ 12.5 mm

$$\cos \Theta = \frac{10.5}{12.5} = 0.84000$$

$$\Theta = 32.86°$$

$$2\Theta = 65.72°$$

$$= 1.155 \text{ radians}$$

$$\text{arc length} = 1.155 \times 12.5 \text{ mm}$$

$$= 14.444 \text{ mm}$$

*The dimensions shown in Figure 1-C have been purposely exaggerated; they are not drawn to scale.

Thus, by flattening the side of the sphere with a cylindrical surface, the axial diameter of the sphere will necessarily elongate by approximately the difference between the arc length and chord length $2a$ or 14.44 − 13.56 = 0.88 mm. This is shown in Figure 2D. (Each of the small "scleral" segments located at the ends of the flattened portion of the sphere must have an anterior-posterior component which is about 0.44 mm long; thus, the total A-P diameter increases by no more than 0.88 mm. That is, this 0.88 mm increase is a maximum, as the natural curvature and rigidity of normal sclera would create a bulge at the "band" edge and would probably allow expansion of the total A-P diameter by only about 0.7 mm. In any case, the 2 mm of compression by such a wide "band" demonstrates how this sphere (with an unstretchable surface) would be elongated by about 0.8 mm. Were this elongation to occur in a comparable fashion in a human eye, this axial increase alone would create about 2 diopters of myopia.

This example (using such an unrealistic band) was chosen to provide an indication of the degree of maximal elongation. For a more realistic situation, we present calculations for a circumferential silastic #40 band, which induces a different reaction in our "model eye." The dimensions of the standard #40 MIRA* silastic band are 2 mm in width and 0.75 mm in thickness. We will assume this band (see Figure 2E) indents the model sphere by the same 2 mm indentation used above.

Prior to performing any calculations, we must know how wide a surface disturbance is created by the 2 mm encircling band. By actual measurements on our indented eyebank eyes, the mean width W of surface curvature disturbance under the 2 mm wide band was 4.1 mm. Though in this situation the true scleral surface was irregularly curved (as shown in Figure 2E), assume for simplicity that the lines shown as curved are really straight lines (Figure 2F), an assumption which will only cause our final calculations to err on the understatement side. In this simplification, the shape of the indented surface (Figures 2F and 2G) is trapezoidal on cross section, with the dimensions of 4.1 mm (base), 2 mm (altitude), and 2 mm for the width of the indented surface. The length of the trapezoidal side x of this geometric figure (Figure 2F) is determined simply by the Pythagorean theorem:

$$x^2 = 2^2 + (1.05)^2$$

$$x^2 = 4 + 1.10$$

$$x^2 = 5.10$$

$$x = 2.26 \text{ mm}$$

*Medical Instrument Research Associates (Boston)

Thus, in the schematic diagram (Figures 2F and 2G), the portion of the indented perimeter indicated by the bolder lines is 2.26 + 2.26 + 2.0 = 6.52 mm. Recall that, prior to any indentation, that 6.52 mm existed in the plane of the curved "scleral" surface. After this indentation, however, that 6.52 mm of perimeter has been "squeezed down" into an A-P dimension of only 4.1 mm width; 2.42 mm are "lost" here. Actually, this "squeezing" actively takes place at two locations in the plane of the diagram in Figure 2E. There is a comparable one below which is not shown. Thus, a total of 2.42 times 2 or 4.84 mm of perimetric circumference are "lost" by the 2 mm of indentation.

The circumference of the plane indicated in the original spherical model (Figure 2A) which had a radius of curvature of 12.5 mm is $C = 2\pi r = 2\pi \times 12.5 = 78.54$ mm. Since the band encirclement shortens this circumference to 78.54 − 4.84 or 73.70 mm, the resulting figure (if we assume an approximately spherical shape) would have to have a new A-P axial diameter d as follows:

$$C = 2\pi r = \pi d; \qquad d = \frac{73.70}{\pi} = 23.46 \text{ mm}$$

Thus, in this schematic analysis, a 2 mm indentation by a circumferential #40 band would shorten the axial length by 25.00 − 23.46 or 1.54 mm. If this alone were the factor responsible for refractive error, it would make the banded globe about 4 diopters hyperopic. Needless to say, our clinical experience presented at the outset indicates that this particular value would be an unlikely refractive error induction. However, the schematic analysis does show that a circumferential band can physically shorten the axial length of an eye.

Utilizing a similar mathematical analysis, we found that a circumferential band indentation which provides a "low push" (less than the 2 mm shown here which we consider "high") *lengthens* the axial length (very much like the ultrawide 15 mm band in the previous example). It is only when the push by the 2 mm band is "high" that the globe shortens. These computations, then, also corroborate the preceding *in vitro* eyebank globe experiments.

Most ophthalmologists have been deluded by the "wives' tale" which expounds that a circumferential band, through its equatorial constricting effect, will obligatorily only lengthen the axial length of an eye (much as an elastic balloon would act under similar mechanical pressures). This *per se* would lead to the induction of a myopic shift in the refractive error. It is common optical knowledge, that with the total refractive power of an eye remaining constant, when the axial length is increased, the eye's refractive error will shift towards myopia; when it is shortened, the shift will be towards hyperopia. We have presented clinical, laboratory, and mathematical evidence that there is a graded axial lengthening which reverses with "high" indentations and increases the likelihood of producing a hyperopic refractive shift with those indentations. These findings help explain the refractive shifts discovered in our retrospective clinical study.

OPTICAL ANALYSES

Following our description of the effect on axial length by a constricting equatorial band, we will now examine the optical consequences of these variations. Moreover, as a by-product of this examination, we will elucidate the discrepancy in the amounts of induced refractive error between the phakic and the aphakic states as found in our initial clinical study. That is, we will be able to answer the questions, "Why does the aphakic eye seem to acquire less of a myopic shift than the phakic eye from the same apparent amount of indentation?" and "Can this be explained on an optical basis alone, or must one postulate a difference in the aphakic eye's response to the encircling element (such as via a change in scleral rigidity) which might cause it to yield, for a comparable indentation, a different elongation than does the phakic eye?"

To serve as the starting point, we undertook some optical constructions. Had one needed to obtain very accurate optical insights, the technique of "optical ray tracing" could be used, with its attendent application of Snell's law of refraction to sets of object rays arriving at various inclinations to each of the main ocular refractive surfaces. However, such constructions are much more appropriate for the analyses of man-made optical systems, with clearly identifiable refractive surfaces, and separated by known, regular indices of refraction. For the eye, though such calculations might be made, they would be time consuming and not really accurate since measurements of the dependent variables are not readily available. The index of refraction of the lens, for example, is not regular — to use available figures necessarily entails approximations anyway. Thus, we might as well choose a "model" — the Gullstrand Schematic Eye (GSE) and its carefully derived constants, which are familiar, highly pragmatic approximations. We will use the GSE to represent the human eye in these calculations. Furthermore, only "first-order" optics, those dealing with the paraxial rays, will be considered here, since further embellishments would serve no useful purpose and would complicate the mathematics unnecessarily; that is, "third order" aberrational analysis is not required. In the forthcoming computations, we have adhered to the "light convention" signs and the letter-symbols signifying power, object and image distances, vergences, and other optical considerations as detailed by Rubin.[25]

In these calculations, we have determined the amount of refractive error produced in the schematic eye distorted by an encircling band; we assumed it lengthened or shortened the eye (or shifted the lens position). The refractive powers of each of the four optical surfaces were determined to three significant figures and all object and image distances were calculated to tenths of a millimeter.

The refractive errors induced by the axial changes were determined as follows: the "retinal" surface (actually the axial point of the retinal surface) was taken as "an object" and imaged successively by each of the four primary refractive surfaces of the GSE. The final image point created by all four optical surfaces is by definition the "far point" of that eye. The reciprocal of the metric distance between that "far point" and the anterior corneal surface is here our definition of the eye's refractive error. The cornea rather than the primary principal plane was chosen as the reference plane for convenience. The refractive errors in each example are compared to the baseline (uninfluenced, undistorted) ocular refractive state. A large series of sample calculations was performed for both phakic and aphakic situations — only one set of these is detailed herein.

THE PHAKIC SCHEMATIC EYE

For each of the following optical analyses the GSE constants given by Ogle[26] were used. However, since he carried the surface powers to only one decimal place, we recalculated them to three. From Ogle,

Radii of curvature

P_4 is the power of the posterior surface of the lens; $r_4 = +6.0$ mm;

P_3 is the power of the anterior surface of the lens; $r_3 = -10.0$ mm;

P_2 is the power of the posterior surface of the cornea; $r_2 = -6.8$ mm;

P_1 is the power of the anterior surface of the cornea; $r_1 = -7.7$ mm;

Indices of refraction

$n_{vitreous} = 1.336$

$n_{lens} = 1.410$

$n_{aqueous} = 1.336$

$n_{cornea} = 1.376$

Distances

Thickness of cornea	= 0.5 mm
Depth of anterior chamber	= 3.1 mm
Thickness of lens	= 3.6 mm
Secondary focal point to posterior lens surface	= 17.1 mm
Total axial length of GSE	= 24.3 mm

The powers of each of the primary surfaces can now be calculated:

$$P_4 = \frac{n' - n}{r_4} = \frac{1.410 - 1.336}{.006} = \frac{.074}{.006} = +\ 12.333\ \mathrm{D}$$

$$P_3 = \frac{n' - n}{r_3} = \frac{1.336 - 1.410}{.010} = \frac{-.074}{-.010} = +\ 7.400\ \mathrm{D}$$

$$P_2 = \frac{n' - n}{r_2} = \frac{1.376 - 1.336}{-.0068} = \frac{.040}{-.0068} = -\ 5.882\ \mathrm{D}$$

$$P_1 = \frac{n' - n}{r_1} = \frac{1.000 - 1.376}{-.0077} = \frac{-0.376}{-.0077} = +\ 48.831\ \mathrm{D}$$

The first object-image challenge was to image the "normal" GSE's secondary focal point (F'), assumed to lie on the retina, through the system of each of the four refractive surfaces.

$$u_4 = -\ 17.10\ \mathrm{mm};\ U_4 = -\frac{n}{u} = -\ \frac{1.336}{.0171} = -\ 78.129\ \mathrm{D}$$

$$U_4 + P_4 = V_4$$

$$-\ 78.129 + 12.333 = V_4 = -\ 65.796\ \mathrm{D};\ v_4 = \frac{1.41}{-65.796} = -\ 0.0214\ \text{meters}$$

$$u_3 = -\ |\ 21.4\ \mathrm{mm} + 3.6\ \mathrm{mm}\ | = -\ 25.0\ \mathrm{mm};\ U_3 = \frac{-1.41}{0.025} = -\ 56.400\ \mathrm{D}$$

$$U_3 + P_3 = V_3$$

$$-56.400 + 7.400 = V_3 = 49.00; v_3 = \frac{1.336}{-49.00} = -0.0273 = 27.3 \text{ mm}$$

$$u_2 = -\mid 27.3 \text{ mm} + 3.1 \text{ mm} \mid = -30.4; U_2 = \frac{1.336}{-0.0304} = -43.947 \text{ D}$$

$$U_2 + P_2 = V_2$$

$$-43.947 - 5.882 = V_2 = -49.829; v_2 = \frac{1.376}{-49.829} = -0.0276 = -27.6 \text{ mm}$$

$$u_1 = -\mid 27.6 + 0.5 \mid = -28.1 \text{ mm}; U_1 = \frac{1.376}{-.0281} = -48.968 \text{ D}$$

$$U_1 + P_1 = V_1$$

$$-48.968 + 48.831 = V_1 = -0.1370 \text{ D}$$

Thus, the GSE is 0.137 D hyperopic. This is the "baseline" error against which the elongated phakic eye will be compared.

Arbitrarily, we assumed that this model eye would undergo a 1 mm axial elongation due to the circumferential, equatorial encircling band. In view of the 1.09 mm elongation produced by the "moderate" band indentation in the *in vitro* eyebank eye experiments (Table IX), this is not an unreasonable assumption. However, yet another assumption is made — that the elongation is confined to the posterior half of the eye, so the anterior chamber depth is assumed to remain unaffected by the constricting band. We will soon see that this is not true. The circumferential band actually creates a forward shifting of the lens and a reduction of the anterior chamber depth. This fact actually exaggerates further what will be demonstrated here and makes our point even stronger; however, this last revelation gets ahead of our story.

We will proceed through a similar set of calculations as previously; again u_4 is the distance between the eye's retinal surface and the posterior lens surface. Since we have increased this distance by 1 mm, $u_4 = -18.10$ mm instead of the GSE distance of -17.1 mm.

$$u_4 = -18.10 \text{ mm}; U_4 = \frac{1.336}{-.01810} = -73.812 \text{ D}$$

$$U_4 + P_4 = V_4; -73.812 + 12.333 = -61.479 = V_4; v_4 = \frac{1.41}{-61.479} = -22.9 \text{ mm}$$

$$u_3 = -|22.9 + 3.6| = -26.5; U_3 = \frac{1.41}{-.0265} = -53.208 \text{ D}$$

$$U_3 + P_3 = V_3; -53.208 + 7.400 = V_3 = -45.808; v_3 = \frac{1.336}{-45.808} = -29.2 \text{ mm}$$

$$u_2 = -|29.2 + 3.1| = -32.3 \text{ mm}; U_2 = \frac{1.336}{-.0323} = -41.362$$

$$U_2 = P_2 = V_2; -41.362 - 5.882 = V_2 = -47.244; v_2 = \frac{1.376}{-47.244} = -29.1 \text{ mm}$$

$$u_1 = -|29.1 + 0.5| = -29.6 \text{ mm}; U_1 = \frac{1.376}{-.0296} = -46.486$$

$$U_1 + P_1 = V_1$$

$$-46.486 + 48.831 = V_1 = +2.345$$

The final image vergence V_1 is + 2.345 D and this signifies the eye is 2.345 D myopic. However, to learn how much change was induced by the 1 mm of elongation, we must compare this figure to the "baseline" GSE, which is .137 D hyperopic. Thus, the axial length increase of 1 mm has changed the power of the GSE by 2.482 D in a myopic direction.

Again, this refractive error is calculated using the anterior corneal surface as a reference plane. Later, in Tables X and XI, the error will also be referred to the more useful, "spectable lens plane" for the general comparisons.

THE APHAKIC SCHEMATIC EYE

Next we determined, through a similar set of calculations, the aphakic situation. To find the baseline power of the aphakic eye, we assumed the aphakic eye was a standard GSE with its lens removed; that is, the other measurements remained as they were. Our calculations proved this eye to be 11.786 D hyperopic with the error referred to the anterior corneal surface. As with the phakic example, we then assumed that an equatorial band's effect was simply to elongate the aphakic eye by 1 mm. Recalculation showed this elongated aphakic eye to have a refractive error of 9.722 D hyperopia (See Table X). In other words, the 1 mm increase

TABLE X: CACULATED REFRACTIVE ERROR (DIOPTERS) INDUCED BY ENCIRCLEMENT PRODUCING 1 MM ELONGATION

	Phakic			Aphakic			Phakic Minus Aphakic
	Before Encirclement	After Encirclement	Net Myopic Shift	Before Encirclement	After Encirclement	Net Myopic Shift	Myopic Shift Difference
At corneal plane	−0.137	+2.345	+2.482	−11.786	−9.722	+2.064	.418
At spectacle lens plane	−0.137	+2.427	+2.564	−10.101	−8.547	+1.554	1.010

TABLE XI: REFRACTIVE ERROR (DIOPTERS) INDUCED BY ELONGATION

	Phakic			Aphakic		
mm Elongation	At Cornea	At Spectacle Plane	Difference (at spec. plane)	At Cornea	At Spectacle Plane	Difference (at spec. plane)
−2	−5.772	−5.339		−16.693	−13.532	
			2.733			1.627
−1	−2.705	−2.606		−14.288	−11.905	
			2.472			1.804
0	−0.137	−0.137		−11.786	−10.101	
			2.564			1.554
1	+2.345	+2.427		−9.722	−8.547	
			2.624			1.698
2	+4.728	+5.051		−7.562	−6.849	
			2.412			1.501
3	+6.751	+7.463		−5.772	−5.348	
			2.741			1.472
4	+8.947	+10.204		−4.092	−3.876	
			2.406			1.449
5	+10.715	+12.610		−2.512	−2.427	
			2.588			1.418
6	+12.525	+15.198		−1.024	−1.009	
			2.344			1.391
7	+14.083	+17.544		+0.380	+0.382	
			Mean 2.543			Mean 1.546

in the axial length in the aphakic eye produced a shift in a myopic direction of 2.064 D; yet that same 1 mm elongation in the phakic eye (determined just previously) produced 2.482 D myopic shift. Significantly, the aphakic eye encountered 0.418 D less of a myopic shift.

As repeatedly mentioned, these calculations are based on a corneal reference plane for the refractive error. The difference between the refractive errors induced in the phakic and aphakic states are still more apparent when we refer them to the "spectacle plane", which of course, is where most clinicians examine for the error. Table X also shows that, optically, 1 mm of axial elongation produces 2.564 D of myopic shift at the spectacle plane in the phakic eye, but only 1.554 D in the aphakic eye — a difference now of 1.010 D!

These simple optical calculations then suffice to explain the primary phakic versus aphakic difference found in our clinical study as well as in Jacklin's[7]; that is, the phakic eye attains more myopic shift than the aphakic eye from a given axial elongation. But, does this simple optical explanation account for all of it? A later section, "lens shift," will help answer this question.

The 1 mm of axial elongation used in the demonstration calculations to construct Table X was chosen simply as one fairly typical example on which to base a general statement about the relative induction of refractive error by the phakic and aphakic states. Actually, (perhaps surprisingly) the amount of preoperative refractive error does not significantly influence the resultant comparison. Table XI collates an enormous number of individual calculations. Each individual datum in this table represents a comparable series of calculations to those shown in the previous numerical, object-image examples. This table shows the refractive errors induced by eleven 1 mm increments in axial length in both phakia and aphakia. Note that, though the effect of elongation (or shortening) on the error does vary somewhat depending on the chosen baseline axial length, the main difference is found only between the phakic and aphakic states. For example, from Table XI, for the phakic eye which preoperatively happens to be axially longer than the GSE by 2 mm, the "pre-elongation" correction (in the spectacle plane) is 5.051 D of myopia. If the encircling element than elongates this same eye by only 1 mm, the new myopic refractive error is 7.463 D — an increase in its myopia of 2.412 D. If this same eye (longer than the GSE by 2 mm) had the lens extracted, its new refractive eror would be 6.849 D hyperopia. With 1 mm of axial elongation, the hyperopic correction in this eye would be reduced to only 5.348 D, signifying 1.501 D of myopic shift in contrast to the 2.412 D shift induced in the phakic eye. Thus, Table XI indicates that even with the presence of large preoperative axial refractive errors, the myopic shift induced by an additional 1 mm of elongation is not too different from that induced in eyes with low degrees of preoperative error. This is true for both phakia and aphakia.

Another way of looking at the data in Table XI emphasizes the fact that the dioptric difference between comparably elongated aphakic and phakic eyes is relatively constant. In the preceding example, there is about 1.5 D difference between the two types of eyes. This calculated difference would have been less if the induced axial elongation selected was less than 1 mm, which in retrospect, might have been a more realistic estimate considering the results of our clinical study (in contrast to our *in vitro* study results). Note: our actual clinical difference (Table IV) was 0.8 D.

The refractive error of any eye depends on both the axial length and the refractive powers of the ocular components; but the calculations leading to Tables X and XI presume a variation only in the axial length. Still, these numbers are interesting for comparative purposes since they give us some insight as to the effect of pure axial elongation. Obviously, a clinical examination yields only a specific refractive error and does not reveal that eye's true overall power nor that of the component surface powers. Nor does it indicate what the axial length is. Clinically, we can easily determine only the error itself, created by the imperfect coordination of these parameters (Rubin[25]).

Actually, we know that almost all refractive errors are likely to include some effect by each parameter. We anticipated being able to discover the extent of each of these effects on the refractive error of the individual eye. We had on hand what was felt to be an exciting, objective way to measure the axial length and lens displacement (to be discussed later) *in vivo* — the ultrasonogram (both A-scan and B-scan). However, just as with our *in vitro* measurements with these instruments, we were greatly disappointed as we found our variation in reading error with the A-scan (the B-scan allowing even less accuracy) to be no better than ± 1.0 mm. Ossoinig[27] feels this can be reduced to ± 0.1 mm with the Kretz A-scan unit. However, in a few trials, we found we could do no better than ± 0.4 mm. Such a "reading error" translated into induced refractive error would correspond to approximately ± 1.2 D — too great a deviation to allow us to substantiate some of the less extensive refractive changes found. Thus we did not use ultrasonograms in this study. However, it is probable that with practice, our reading error will decrease; so we do plan on obtaining the Kretz unit to use in additional studies. But we still fear it will not allow a substantial refinement of the data given here to be of significant help in adding further corroboration to these findings.

THE LENS SHIFT

Through all the foregoing calculations, we have assumed that when the equatorial band increases the eye's total axial length by 1 mm, it does so by increasing only the dimension between the posterior lens surface and the retina. What is indeed a further theoretical possibility is that the band constriction also "pushes" the lens forward towards the cornea, thereby shallowing the anterior chamber slightly. Let us first assume the latter does indeed occur.

OPTICAL STUDY

To determine the amount of optical effect such a lens shift will induce, let us hypothesize that the lens will move forward a distance of only 0.3 mm. This is assumed to occur in addition to the 1 mm of total axial elongation. So, this internal shift will create an even longer distance between the posterior lens surface and the retina. The new axial dimensions so created would be as follows:

corneal thickness	0.5 mm
anterior chamber depth	2.8 (0.3 mm shorter than the GSE)
lens thickness	3.6
lens to retina distance	18.4 (1.3 mm longer than the GSE)
total axial length	25.3 (1 mm longer than the GSE)

$$u_4 = -\ 18.4 \text{ mm},\ \ n_v = 1.336;\ U_4 = \frac{1.336}{-.0184} = -\ 72.609 \text{ D}$$

$$U_4 + P_4 = V_4; -72.609 + 12.333 = V_4 = -60.276; v_4 = \frac{1.41}{-60.276} = -23.4 \text{ mm}$$

$$u_3 = -\ |23.4 + 3.6| = -\ 27.0;\ U_3 = \frac{1.41}{-.0270} = -\ 52.222 \text{ D}$$

$$U_3 + P_3 = V_3 = -52.222 + 7.4 = V_3 = -44.882; v_3 = \frac{1.336}{-44.822} = -\ 29.8 \text{ mm}$$

$$u_2 = -\ |29.8 + 2.8| = -\ 32.6 \text{ mm};\ U_2 = \frac{1.336}{-.0326} = -\ 40.982 \text{ D}$$

$$U_2 + P_2 = V_2 = -40.982 - 5.882 = 46.864 = V_2; v_2 = \frac{1.376}{-46.864} = -29.4 \text{ mm}$$

$$u_1 = -\ |29.4 + 0.5| = -\ 29.9 \text{ mm};\ U_1 = \frac{1.376}{-.0299} = -\ 46.020 \text{ D}$$

$$U_1 + P_1 = V_1 = -\ 46.020 + 48.831 = +\ 2.811 \text{ D}$$

TABLE XII: MYOPIC REFRACTIVE ERROR (IN DIOPTERS) PRODUCED BY LENS SHIFT IN A 1 MM ELONGATED GSE

	Lens Shift (mm anteriorly)				
	0	0.1	0.3	0.5	0.7
At corneal plane	2.345	2.501	2.811	2.964	2.268
At spectacle plane	2.427	2.592	2.926	3.092	3.425
Net change in refractive error from GSE (at corneal plane)	2.482	2.638	2.948	3.101	3.405
Net change in refractive error from GSE (at spectacle plane)	2.564	2.729	3.063	3.229	3.562
Myopic difference induced by forward shift of lens					
At corneal plane	0	0.156	0.466	0.619	0.923
At spectacle plane	0	0.165	0.499	0.665	0.998

This eye is 2.811 D myopic, or 2.948 D more myopic than the GSE. Comparing this to the eye with 1 mm of elongation but with no lens shift, we find this 0.3 mm lens shift induces 2.948 − 2.482 = 0.446 D more myopia at the corneal plane. Thus only 0.3 mm of anterior lens displacement will add about 0.5 D of power to an eye.

In Table XII we have calculated the optical effects of other shifts in lens position, assuming the total axial length continues to remain 1 mm longer than the GSE. These refractive errors have been determined at both the corneal and the spectable reference planes for the absolute errors created by the lens shifts as well as the errors compared to the GSE baseline. Also shown (at the bottom of the table), is the amount of myopic shift created specifically by the lens shift.

Since such a lens shift can obviously occur only in a phakic eye and any forward lens shift will always increase the myopic error, it is clear that we have elaborated yet another factor which can magnify the refractive error difference between the encircled phakic and aphakic eyes found in our clinical study. However, we so far have simply introduced "lens shift" as a theoretical possibility. We now raise the question as to whether or not it actually occurs. To answer this, we designed another clinical study to measure the anterior chamber depth which indirectly reflects the lens position.

CLINICAL STUDY

In 26 phakic patients, the central anterior chamber depth was measured pre- and postoperatively in the detached as well as in their unoperated, "control" eye. It is well known that the size and shape of an eyeball as well as the depth of the anterior chamber are genetically determined. Thus, there is an extremely high likelihood that the anterior chamber depth in the uninvolved eye will statistically closely represent the chamber depth in the other eye prior to its retinal detachment. Hence one eye readily serves as the baseline "control" for the other. We used a Haag-Streit pachometer with a scale to allow the reading of any depths up to 6.0 mm. Since most patients in this study were older than 50, accommodation was unlikely to play a significant role in influencing their anterior chamber depth. However, to remove any possibility of accommodative variation in those as well as in the younger patients, all eyes were measured under cycloplegia to make the data comparable. Five readings were obtained at each sitting for each eye and the means were utilized for the statistical analyses.

Although in none of these eyes was there any history of trauma, each was carefully gonioscoped to rule out a chamber angle deformity which might influence or distort the interpretation of the measurements.

TABLE XIII: CENTRAL ANTERIOR CHAMBER DEPTH (MM) IN 26 PHAKIC PATIENTS

Control Eye Mean	No.	Preoperative Depth	S D	Postoperative Depth	S D	height of Band Indentation
3.11	15	3.42	.032	3.02	.034	Low
3.09	8	3.65	.045	2.98	.051	Medium
3.13	3	3.74	.071	2.83	.090	High

RESULTS

The test re-test repeatability in reading the pachometric depth scale was ± 0.03 mm. The correlation between the preoperative and postoperative readings (3 months later) on the control eye was 0.91 — an extremely high coefficient, which only emphasizes the significance of the readings given in Table XIII. This table is interesting in a number of aspects: (1) the mean anterior chamber depth (3.10 mm) in the normal eye is surprisingly constant (S D = 0.03). Our mean value is essentially identical to that selected by Gullstrand for his schematic eye constant. (2) The chamber depth was deeper in virtually all the unoperated eyes with detachment than the opposite control eye. This was an unexpected finding; but in addition and still more surprising, the anterior chamber was found to be deeper in those eyes in which we later (at surgery) needed to use a "high" band indention than in those that needed a "low" band! It was as if the preoperative chamber depth predicted the future band height requirement. One possible explanation for this is that we were likely to use a higher buckle in eyes that had very large detachments with a large amount of obvious vitreous traction or preretinal membranes. It was specifically those eyes that preoperatively had deeper anterior chambers. Thus, the high detachment and more extensive vitreous pathology influenced the preoperative depth of the anterior chamber. (3) Following the retinal detachment surgery, in virtually all cases the anterior chamber depth was decreased, but not simply in comparison to its own preoperative depth — to an extent even greater than that in the unoperated, control eye. As might be anticipated, the "high" and "moderate" indentations created somewhat more of an anterior shift in lens position than did the "low" band, but even the "low" band did create a statistically significant (mean) shift of 0.09 mm. As is evident from Table XII, even this small shift could account for about 0.14 D of myopic error.

With "high" indentations, the anterior shift of the lens occurs to a greater degree than with "moderate" or "low" indentations. This tends to counteract somewhat the hyperopic error induced concomitantly by the axial shortening. We have not calculated the exact error for this combination effect since the specific amount is moot. Suffice it to know that, in an eye with "high" indentation, the combination of axial shortening and anterior lens displacement does occur and tends to reduce the overall optical effect of either alone.

In summary, of these clinical, pachometric measurements of the anterior chamber depth, we have confirmed our a priori reasoning and have shown that there is indeed an anterior shift in the position of the human lens following an encircling procedure for retinal detachment. This shift occurs with all equatorial band indentations but the greater shifts occur with the higher indentations.

SUMMARY

GENERAL

This report consists of a retrospective clinical study of the effect of retinal detachment repair, specifically the encircling procedure, on induced spherical refractive error. To analyze the findings we include optical and supplementary clinical and *in vitro* studies of corneal curvature, axial length, and anterior chamber depth. The results of each of these help confirm and are sufficient to explain the discoveries of the orginal clinical study.

SPECIFIC

1. A retrospective clinical study of 1,477 encircling procedures for retinal detachment is reported. A rather high number (41%) of eyes were aphakic which reflects the particular referral population which is especially slanted toward aphakic detachments during the winter-spring months (Table I).
   A. The mean age of the phakic patients with detachment was 55.6; that of the aphakic, 66.9, (Table II).
   B. The mean preoperative refractive error was − 1.91 D (S D = 1.87) in the phakic group and + 8.34 D (S D = 1.52) in the aphakic patients, both of which emphasize the myopic tendency in patients with retinal detachment (Tables IIIA and IIIB).
   C. Postoperatively, the mean shift in refractive error was − 1.70 D (S D = 0.67 D) in the phakic eyes and − 0.91 D (S D = 0.58 D) in the aphakic — that is, a larger myopic shift occurred in the aphakic eyes (Table IV).
   D. The amount of refractive shift was unrelated to the preoperative refractive error (Tables VIA and VIB).
   E. This shift in refractive error was correlated with the height of the encircling indentation; bands giving a "low" and "moderate" indentation yielded respectively more myopic shift; yet "high" indentations tended to give, paradoxically, a hyperopic shift, (Tables V, VIA and VIB).

2. The various parameters influencing these refractive errors were studied:
   A. The corneal curvature was measured in 75 eyes preoperatively and postoperatively and showed that there was no change in the basic corneal power created by the encircling element, though some astigmatic changes were occasionally produced (especially by anteriorly placed buckles). Thus corneal power was not influenced by the band and could not have accounted for the refractive shifts noted in the retrospective clinical study (Tables VIIA, VIIB, and VIII).
   B. The effect of equatorial constriction by an encircling #40 silicone band on the axial length of the eye was studied in 10 eyebank eyes. These studies confirmed the occurrence of an initial golbe elongation which reverted to axial shortening with "high" equatorial indentations (Table IX).
   C. Further analyses by optical constructions using a "model" eye coupled with a large series of optical calculations helped explain

the mechanism of this effect as well as the amount of axial change (Tables X and XI).

D. In another clinical study, the depth of the anterior chamber was pachometrically determined in 26 eyes encircled for repair of their retinal detachments as well as in the contralateral, unoperated eyes, which served as controls. The preoperative depth in an eye with a detached retina was found to be deeper than the control eye, while following the encircling procedure, the anterior chamber became even shallower than the control. This was accounted for by a retrodisplacement of the lens-iris diaphram in the eye as long as its retina was detached; this was followed by an anterior shift in the lens positions after the encirclement. Moreover, eyes which were later to require a "high" indentation, preoperatively were found to have even deeper anterior chambers than those requiring "low" indentations — possibly a predictive sign (Table XIII).

E. Other optical analyses were made to determine the amount of error induced by the lens' anterior movement. This was shown to add to the myopic shift in refractive error produced by the axial elongation alone (Table XII).

3. Overall conclusions: These sets of studies provide a rational optical explanation for the generation of the myopic shift in refractive error created by an encircling equatorial band, which both increases the axial length and shifts the lens forward. Contrary to the belief of most surgeons, "high" equatorial indentations produce a paradoxical shortening of the axial length which changes the induced refractive error toward hyperopia. These investigations also explain the induction of a greater myopic shift in the phakic eye than in the aphakic eye; that is, this is likely due solely to relative optically-determined effects in the two types of eyes. This latter phenomenon is further exaggerated by two additional factors: (1) the lens' anterior shift in the phakic eye, and (2) the clinician's use of the "spectacle plane" as a reference position for expressing the refractive error. Though still other additional factors may be involved in the clinically manifest effects discovered in our clinical study, we feel those delineated are sufficient to explain these findings.

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