SECTION FIVE

Physics of Capsulorrhexis

Stress and Strain

The Continuous Curvilinear Capsulorrhexis (CCC) was independently developed by Drs. Howard Gimbel and Thomas Neuhann; it is universally acknowledged as one of the fundamental elements of modern phaco surgical techniques. An understanding of the dynamics of creating a capsulorrhexis begins with an overview of material analysis. Figure 5-1-1 is a strip of material without any forces acting on it; the interdigitated central portion represents the intermolecular attractions at this location. Figure 5-1-2 depicts the material with very mild force applied as indicated by the arrows; **stress** is the force divided by the cross-sectional area where the force is being applied (the central interdigitated area in this case). In Figure 5-1-3, the stress has increased (bigger arrows) so that the material begins to deform; note the stretching at the center. **Strain** is defined as the change in length of a deformed material divided by its original length. If strain is increased just beyond a material's elastic limit, the material will be permanently deformed even after stress is discontinued. As strain increases further beyond the **elastic limit**, stress usually initially increases slightly but then decreases as the material's breaking point is approached. When this point is reached, the intermolecular bonds are broken and the material tears apart. Note the slightly smaller force arrows in Figure 5-1-4 relative to those in Figure 5-1-3; these smaller arrows represent the force required just prior to the breaking point.

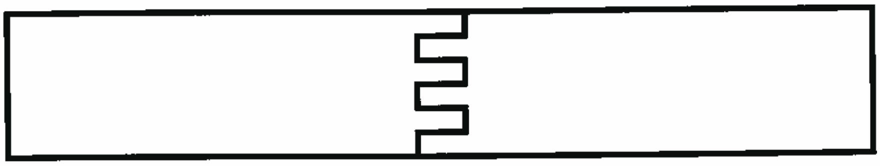


Figure 5-1-1

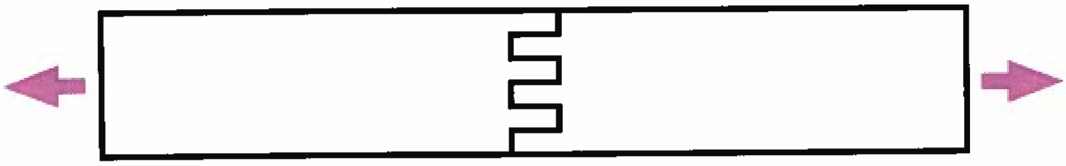


Figure 5-1-2

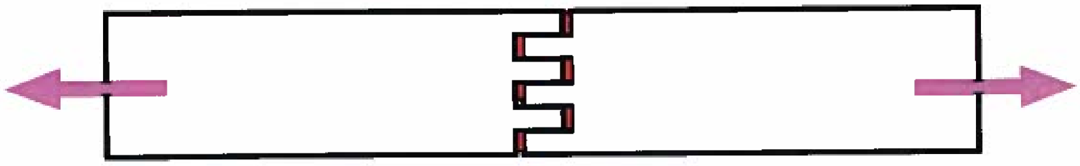


Figure 5-1-3

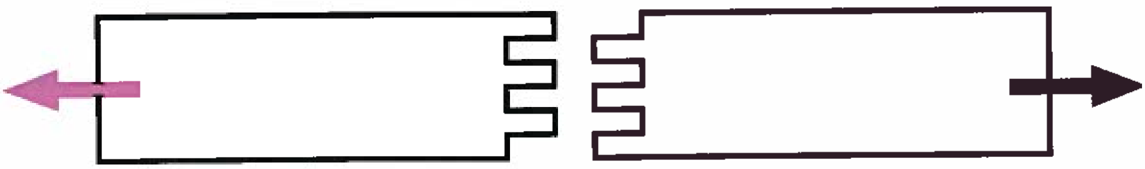


Figure 5-1-4

FIGURE 5-1

Shear vs Rip

Figure 5-2-1 illustrates **shearing** principles. Area x remains stationary while area y is pulled from point a to point b in order to tear this material from point A to point B. All of the pulling force is concentrated at the point of tearing and is in the same direction as the tear. Even though area y may still be engaged by a cystotome or forceps at point b, no further tearing will occur as long as the instrument is not moved. Contrast this with the **ripping** schematic shown in Figure 5-2-2, where area x is again stationary and the material is engaged with an instrument at the blue dot and pulled with vector force t (note the arrows pointing left, which represent the counterforce caused by the left side of the material being stationary). Although no tearing occurs while y is pulled from a toward b, stress and strain in the material progressively increase. When point b is reached, the strain passes the material's breaking point and ripping begins in the direction noted by arrow E. Figure 5-2-2 depicts the material just as ripping begins. Point A has just ripped apart. Point B is undergoing strain. Point C has some stress without any deformation, and point D has no forces acting on it. Note the changes in the points when the rip reaches point B (Figure 5-2-3). Point C, which previously had stress without deformation, now has strain. Point D, which formerly had no forces acting on it, now has stress. The rip will tend to propagate in this fashion as long as area y is held firmly at point b, even though it is not being moved any further. Recall that the stress required at the breaking point is less than that required to reach the breaking point; the surplus force fuels the tear's propagation.

Therefore, ripping the capsule is less desirable than shearing for two reasons. First, the tear tends to uncontrollably extend when ripping even when the grasping instrument is held stationary. Second, more force is generally needed to begin a tear with ripping as opposed to shearing because the force is distributed over a larger area with ripping (ie, at points A, B, and C in 5-2-2) relative to the concentration of force just at the point of tearing with shearing (point A in Figure 5-2-1). Moreover, only a component vector (t_1) of the pulling force pulls the material apart with ripping while the residual force (t_2) serves to direct the rip in direction E; contrast this to the efficiency in shearing of all of the pulling force being utilized in the direction of the tear.

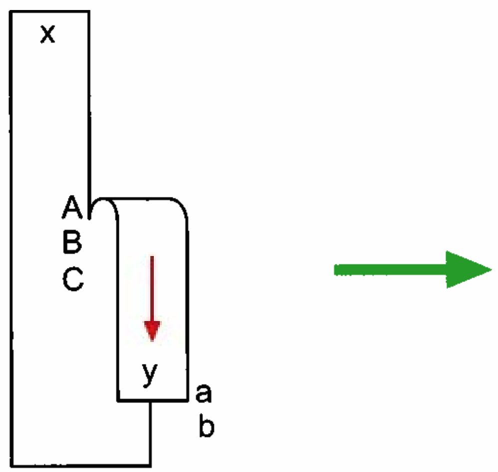


Figure 5-2-1

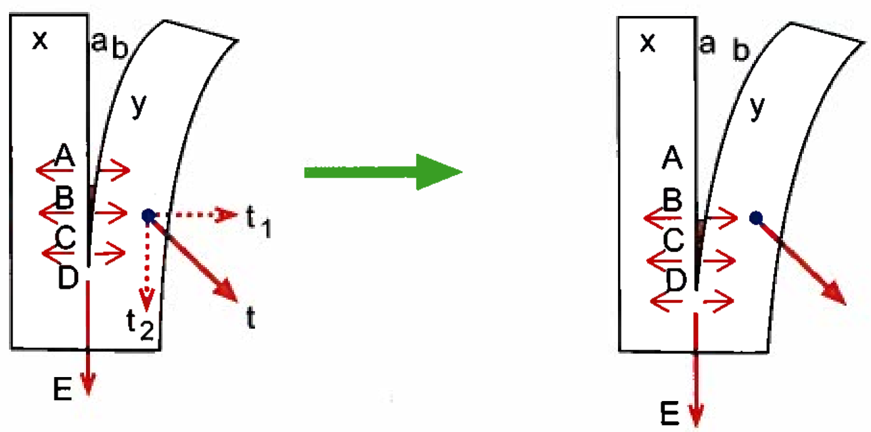


Figure 5-2-2

Figure 5-2-3

FIGURE 5-2

Capsulorrhexis with Shearing

Capsulorrhexis often begins with the formation of a flap as in Figure 5-3-1. The cystotome enters at point 1 and then proceeds to point 4 using either small, connecting can-opener bites or a side-cutting cystotome. At point 4, the cystotome is pulled in the direction of the blue arrow to create a capsular flap, which is then folded over to lay on top of intact anterior capsule as shown. The flap is engaged with a cystotome or capsular forceps at the blue dot at point y and pulled in the direction of the curved green arrow. When using a cystotome, press only hard enough to engage and move the flap; too much force may penetrate the flap, thus inadvertently cutting the intact capsule beneath as well as retarding progression of the flap because of resistance created by engaged cortex. Note that point y is somewhat inside of the peripheral edge of the flap in order to provide a safety margin against the cystotome slipping peripherally off of the flap and damaging intact capsule.

Figure 5-3-2 shows further progress. Notice the symmetry around point a. The flap is a mirror image of the area of capsulorrhexis performed thus far; furthermore, it provides a template showing where the capsulorrhexis will proceed. The flap is grasped at point y and pulled in a curvilinear fashion as shown. Figure 5-3-3 shows the capsulorrhexis one third completed. Notice how the point of instrument engagement (y) is adjusted to stay 2 to 3 clock hours away from the point of shearing. If the instrument were instead placed closer, such as point z, an artifactual stress line (green dashed line) could be created which would compromise the predictability of the direction of shear propagation.

Compare the flap positions in Figures 5-3-2 and 5-3-4. Note the loss of symmetry around point a in Figure 5-3-4, which has more of a bullet-shaped configuration relative to the continuous mirror-image curve through point a in Figure 5-3-2. The reason for the difference is that the flap has not been spread out flat in Figure 5-3-4 (note the folds in the flap). If this flap is engaged at point y and pulled as shown, the capsulorrhexis shear will proceed but with a smaller radius than in Figure 5-3-2. Sometimes you may elect to purposely change the size of the capsulorrhexis in this manner, but be aware that only gradual changes in curvature are practical when utilizing shearing. If the flap is pulled to make an even smaller capsulorrhexis than Figure 5-3-4 (ie, a more pointed bullet shape at point a), a distortion is induced at point a which converts the shear to a modified rip which often propagates peripherally. Abrupt changes in the direction of the tear are best accomplished by a planned ripping maneuver as shown in Figure 5-4.

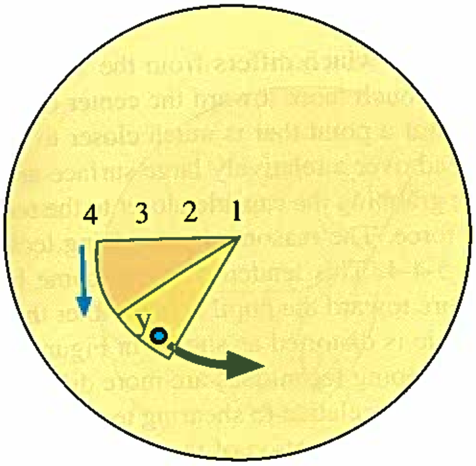


Figure 5-3-1

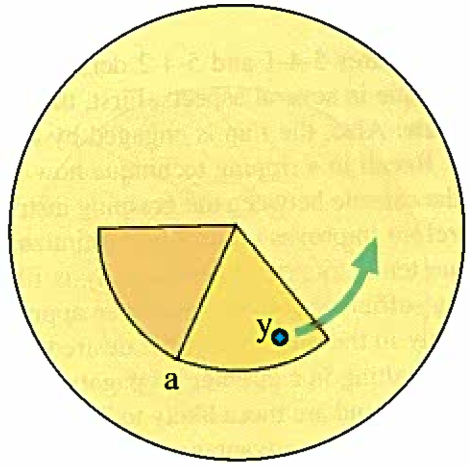
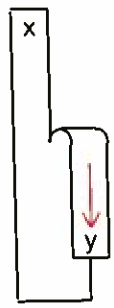


Figure 5-3-2



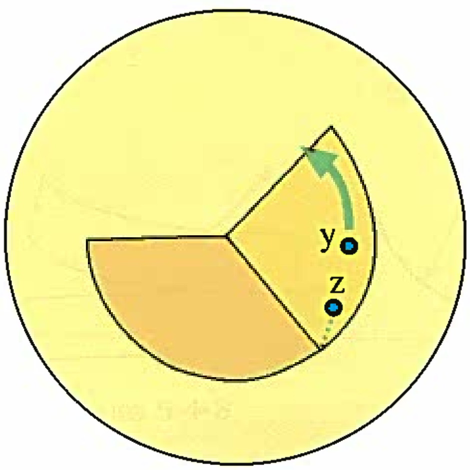


Figure 5-3-3

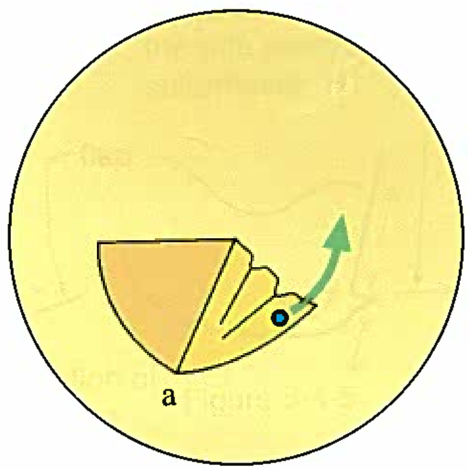


Figure 5-3-4

FIGURE 5-3

Capsulorrhexis with Ripping

Figures 5-4-1 and 5-4-2 demonstrate a ripping technique, which differs from the shearing technique in several aspects. First, the direction of pulling is much more toward the center of the capsule. Also, the flap is engaged by the pulling instrument at a point that is much closer to the tear. Recall in a ripping technique how tearing force is spread over a relatively large surface area of the capsule between the grasping instrument and the tear; grabbing the capsule closer to the tear therefore improves control by minimizing any extraneous force. The reason why a ripping technique tends to extend peripherally is illustrated in Figure 5-4-4. This tendency is overcome by using sufficient pulling force in an appropriate direction (more toward the pupil center rather than directly in the direction of the desired tear) so that the capsule is distorted as shown in Figure 5-4-5, resulting in a circular propagation of the tear. Although ripping techniques are more difficult to control and are more likely to inadvertently extend peripherally relative to shearing techniques, they do have the advantage of enabling more abrupt changes in the direction of the tear.

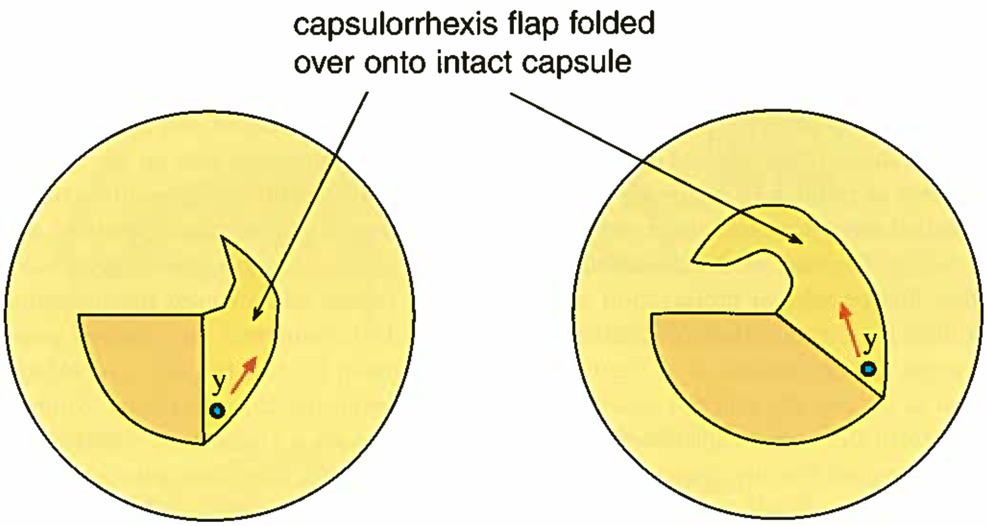


Figure 5-4-1

Figure 5-4-2

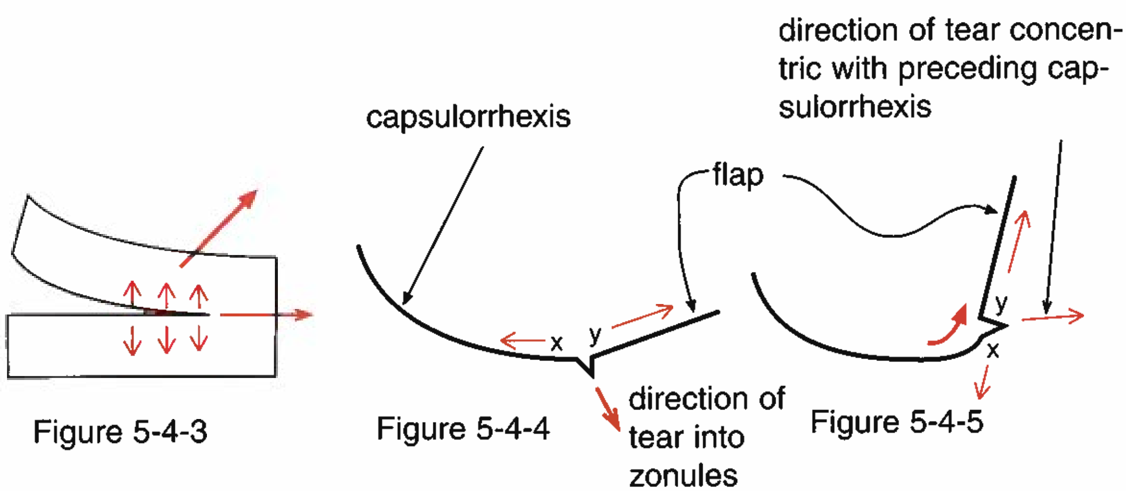


Figure 5-4-3

Figure 5-4-4

Figure 5-4-5

FIGURE 5-4

Maintaining Chamber Depth

A shallow anterior chamber usually indicates that vitreous pressure (red arrow in Figure 5-5-1) is greater than anterior chamber pressure, resulting in the anterior displacement of the lens with zonular stress (blue arrows) as shown in Figure 5-5-1. This stress acts on the site of a capsulorrhexis tear at point x in a ripping configuration that will tend to peripherally extend the tear (green dashed arrow), sometimes even with just maintaining a grip at point y without any pulling (Figure 5-5-2). Because of the sustained zonular forces in this scenario, the surgeon can watch in frustration this peripheral propagation even though he or she has released the instrument grasp from pulling the capsule flap. Viscoelastic may be used to counteract the vitreous pressure and relieve stress on the zonules as in Figure 5-5-3 (red arrows); for this reason, viscoelastic is typically used to deepen the anterior chamber prior to beginning the capsulorrhexis. Some surgeons like to perform the entire capsulorrhexis with a cystotome on a viscoelastic syringe in order to readily compensate for any decrease in anterior chamber depth. Surgeons who prefer using capsulorrhexis forceps should have viscoelastic readily available for injection through the side-port paracentesis incision in case of shallowing of the anterior chamber.

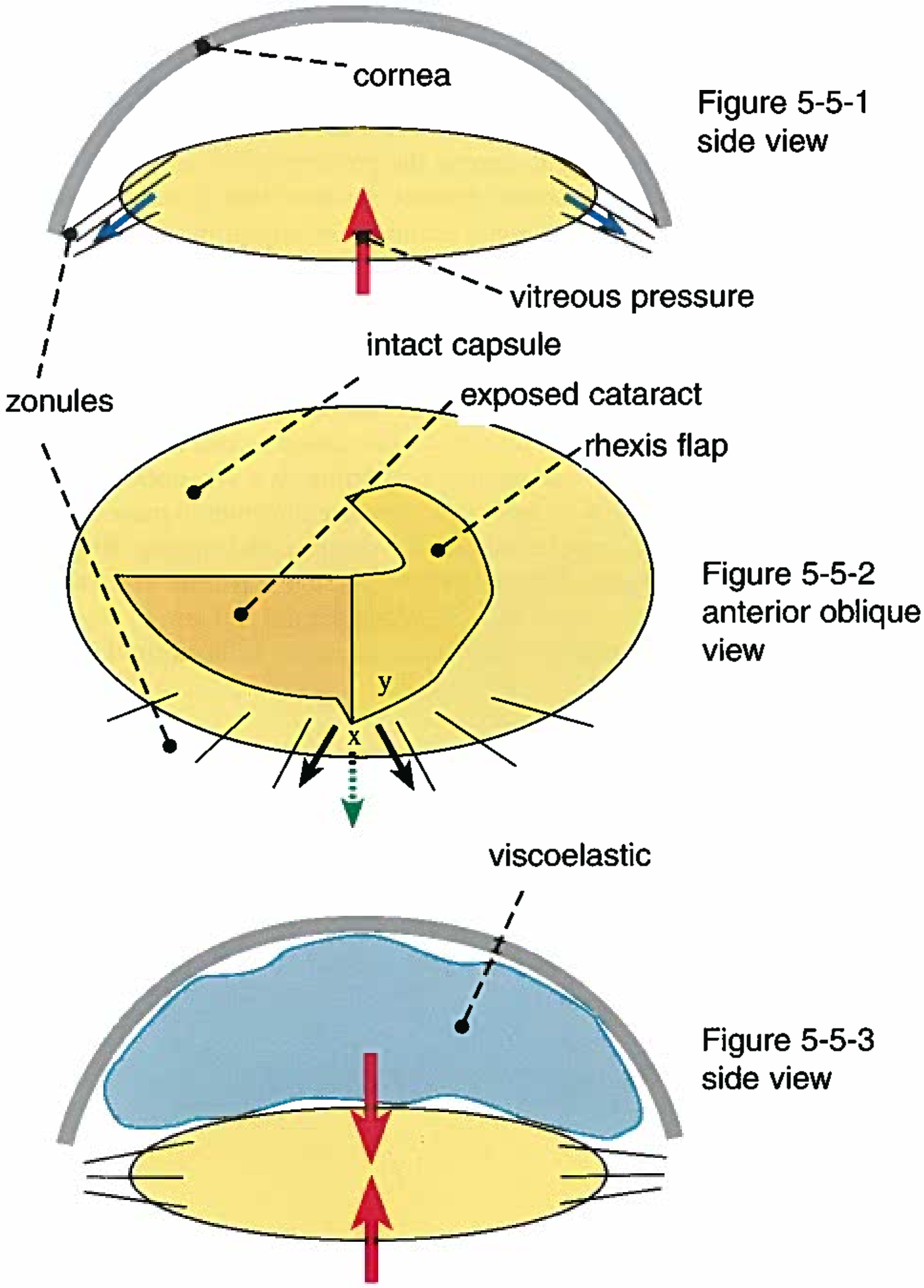

cornea
Figure 5-5-1
side view
vitreous pressure
intact capsule
zonules
exposed cataract
rhexis flap
Figure 5-5-2
anterior oblique
view
y
x
viscoelastic
Figure 5-5-3
side view

FIGURE 5-5

Combining Techniques

Figure 5-6-1 shows a capsulorrhexis proceeding smoothly using a shearing technique; note the smooth mirror-image symmetry around point a. In Figure 5-6-2, a relative shallowing of the anterior chamber contributed to the peripheral extension of the tear. Point b is spear/bullet-shaped instead of smooth and round. Attempting to correct the problem by abruptly changing direction with a shear technique (red arrow) will almost certainly produce more peripheral extension. The better option in this case is to convert to a ripping technique by engaging and pulling as indicated by the blue dot and arrow; viscoelastic is used to reinflate the chamber prior to executing the ripping maneuver. Once a desired configuration is again obtained, you can convert back to a shear technique as illustrated in Figure 5-6-3.

In these situations, the surgeon must be aware if the capsulorrhexis tear has extended into the zonules (typically starting around 8 mm diameter on the anterior capsule). In these cases, excessive pulling (as in a ripping maneuver) can cause the tear to extend around the capsule equator into the posterior capsule. Options in this case include converting to a can opener capsulotomy vs restarting the rhexis from the starting point but in the opposite direction to meet the extension.

Figure 5-6-2 reiterates the different techniques for shearing and ripping. Ripping (blue dot and arrow) has the cystotome or capsule forceps grab the capsule flap close to the tear and pull in a straight direction close to the center visual axis. Shearing (red dot and arrow) engages the flap 2 or 3 clock hours from the tear and pulls in a curvilinear direction in the desired direction of tear propagation.

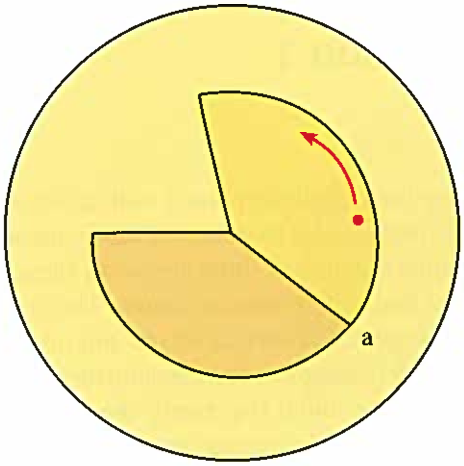


Figure 5-6-1

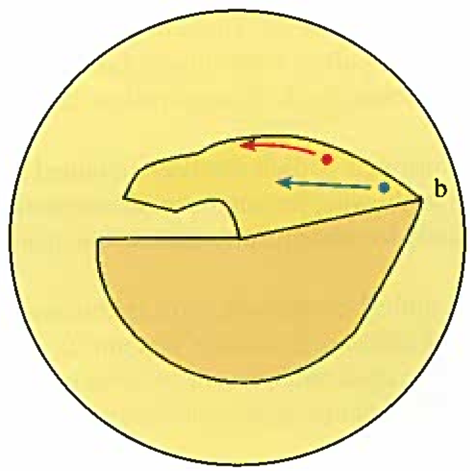


Figure 5-6-2

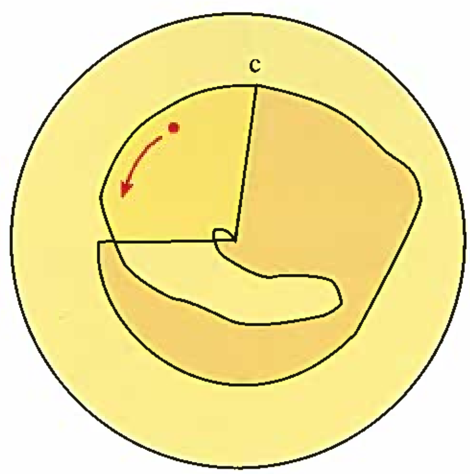


Figure 5-6-3

FIGURE 5-6

Capsulorrhexis Initiation 1

One way to begin the capsulorrhexis is by puncturing the capsule at point 1 with a side-cutting cystotome on a viscoelastic syringe. The cystotome is then moved to point 4, cleanly incising the capsule as it is moved. At point 4, the cystotome is pulled downward (blue arrow) to shear the capsule at this point so that a capsular flap can be created and rolled over as shown. The flap is engaged with forceps or cystotome at point y (originally the posterior surface of the anterior capsule) and pulled in the direction of the curvilinear green arrow to continue the capsulorrhexis with a shearing technique. One problem with this technique is that the initial flap rarely shears exactly in the direction of the blue arrow as shown in Figure 5-7-1. It usually extends somewhat peripherally as shown in Figure 5-7-2. The remedy for this problem is to simply allow for it; point 4 should be central to your desired final diameter. Therefore, when given the configuration in Figure 5-7-2, engage the flap at point y and pull in a curvilinear fashion as depicted by the green arrow. Note that this curved arrow is concentric to the desired path of the capsulorrhexis, which is depicted by the red arrow.

A smaller diameter capsulorrhexis could have been obtained in Figure 5-7-2 by either starting the flap closer to point 3 (thus allowing for some peripheral extension) or pulling the flap more centrally rather than concentrically to consequently redirect the tear more centrally (see Figure 5-3-4).

Note that point 1 is in the optical center; any error in this positioning should be to the right of center. If you err to the left of center (eg, starting at point 2), the resultant flap radius will be constrained such that the resultant capsulorrhexis will be eccentric (to the left) and too small. This error is of course easily rectified by making appropriate relaxing incisions to extend the flap radius to or beyond the center.

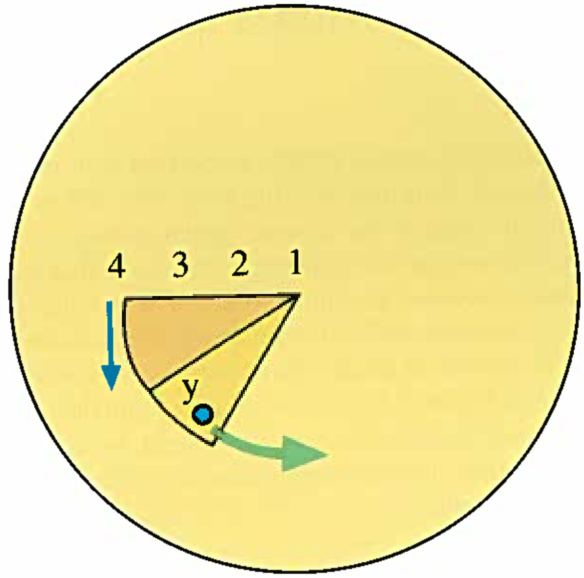


Figure 5-7-1

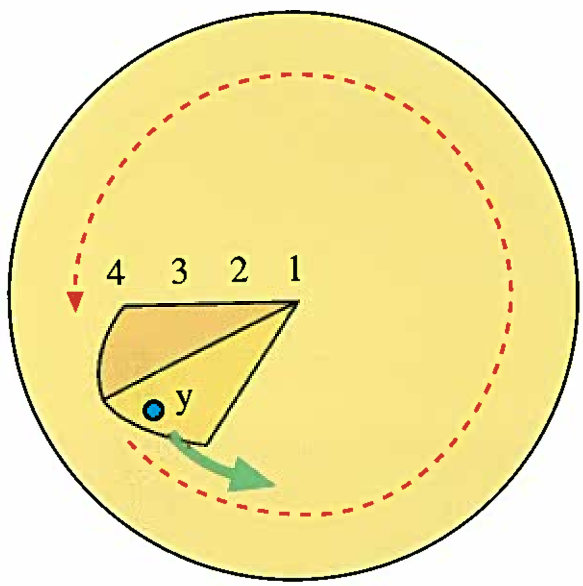


Figure 5-7-2

FIGURE 5-7

Capsulorrhexis Initiation 2

Figure 5-8-1 illustrates the potential pitfalls associated with pulling the capsule at a point central to point 4 (blue arrow). With the shearing force directed as shown by the blue arrow, force is transmitted along the edge of the capsule (green arrows) to both ends of the incision, with consequent potential for peripheral extension of the incision at either end by ripping forces as shown by the red arrows. Extension at point 4 is particularly troublesome because if it extends into the zonules, recovery becomes difficult; conversion to a can-opener capsulotomy is often required in these cases. Extension at point 1 is usually less problematic. In fact, the possible extension at point 1 shown in Figure 5-8-2 can be used to begin the capsulorrhexis by clockwise rotation of the flap as outlined by the red arrow. In general, however, if you wish to shear the capsule at point 4 to begin a flap, the most control can be achieved by pulling the capsule right at point 4 rather than more centrally.

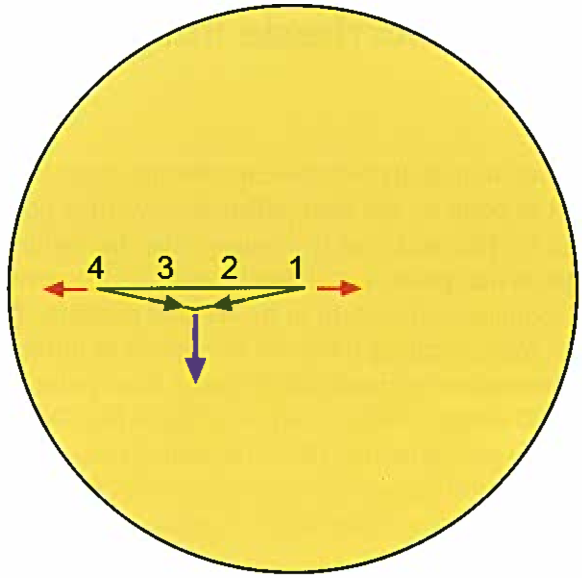


Figure 5-8-1

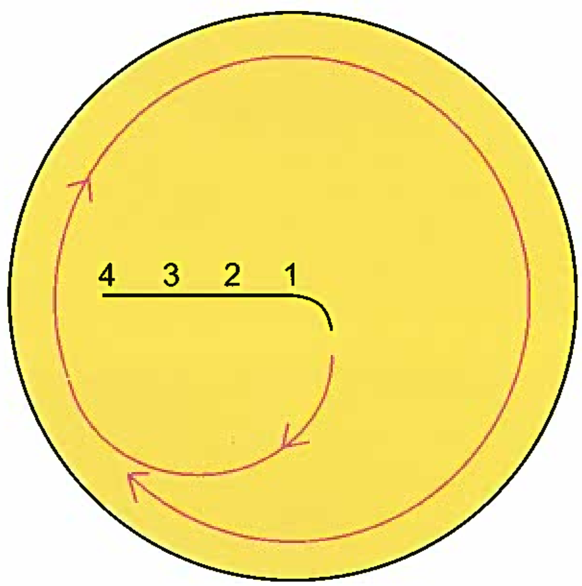


Figure 5-8-2

FIGURE 5-8

Capsulorrhexis Initiation 3

Sometimes it is difficult to initially fold the capsular flap over. In Figure 5-9, the capsule has been incised from point B to point A, and then pulled downward at point A to create the shearing tear from point A to point D. The next goal is to engage the flap (with cystotome or forceps) and fold it over hinge line DB so that point A will overlie point E. However, after thus positioning it, the flap will sometimes spontaneously return to its original position. This tendency can be overcome in a couple of ways. More shearing force can be applied to further extend the tear from A to beyond D. Alternatively, a relaxing incision can be made from point B to point C. The resultant U-shaped flap (CBAD) will usually readily fold over hinge line DC and stabilize in the folded position, whereas the original triangular flap (BAD) tended to return to its in vivo position because of constraint at point B. A helpful adjunct to these maneuvers is to inject additional viscoelastic over the folded flap in order to flatten it and hold it in place.

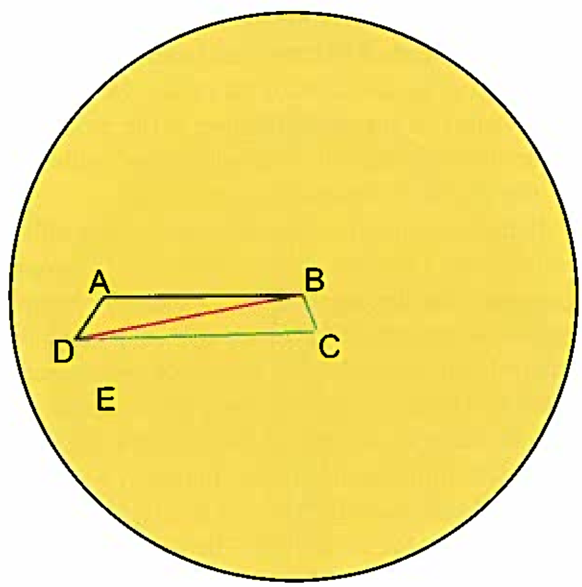


FIGURE 5-9

Capsulorrhexis Initiation 4

An alternate method for beginning the capsulorrhexis is shown in Figure 5-10-1. The capsule has been incised by a cystotome or pinched by a capsulorrhexis forceps at point A; the ensuing triangular flap is grasped at point B and drawn in the direction of the red arrow. Shearing forces are acting roughly equally at points C and D, resulting in a capsule strip with parallel sides. In Figure 5-10-2, the pulling motion has changed to a curvilinear direction (red arrow), which results in the strip changing direction by curving from F to G with point E acting as a central pivot point; the lines EF and EG are radii of curvature for this portion of the tear. At this point, AG can be used as a radius of curvature instead of EG; this has been performed in Figure 5-10-3 where AI and AG (from Figure 5-10-2) serve as new radii of curvature. Notice how the curvilinear red arrow in 5-10-3 reflects this larger radius of curvature relative to the more tightly curved arrow in 5-10-2; these arrows represent the direction that the flap was pulled with either a cystotome or forceps to control the direction of the tear with shearing force utilized.

Point G defines the diameter of the final capsulorrhexis, and although it can be estimated, it is helpful to measure it relative to a desired surgical goal. For example, Dr. Okihiro Nishi's and Dr. David Apple's work suggest that the capsulorrhexis should overlap the anterior surface of the IOL optic such that the posterior square edge, if present, can press into the posterior capsule and more effectively inhibit central lens epithelial cell migration and therefore reduce the incidence of posterior capsule opacification. Therefore, for a 6 mm optic diameter, a 5 mm capsulorrhexis will provide a 0.5 mm overlap. In order to determine the distance from the pupil edge that point G should be placed to achieve a 5 mm capsulorrhexis diameter, a capsule forceps with millimeter markings (eg, **Seibel capsulorrhexis forceps**, Bausch & Lomb Surgical, Rhein Medical) may be used to calibrate the size as shown in Figure 5-10-2. The instrument is placed such that the tip and the 5 mm mark are equidistant from the pupil edge (**purple arrows**), and this distance is used as the guideline for the distance from G to the pupil edge.

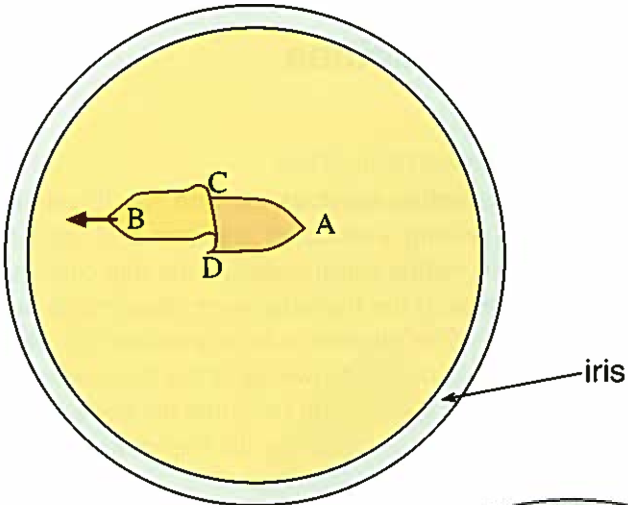


Figure 5-10-1

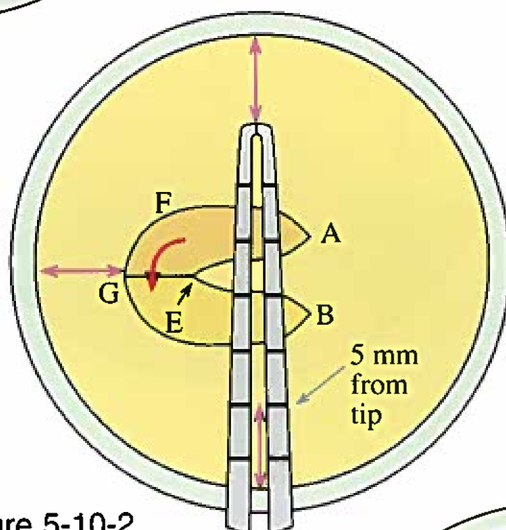


Figure 5-10-2

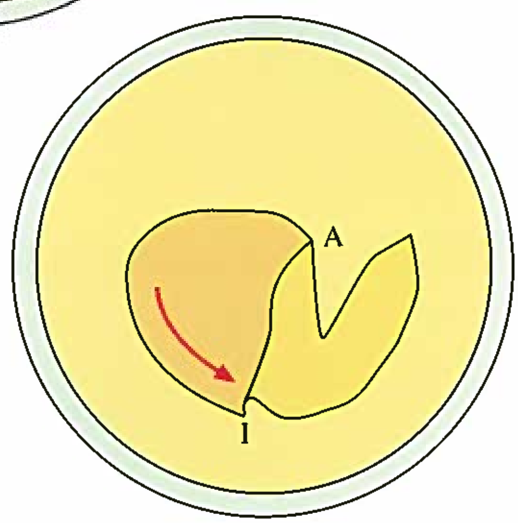


Figure 5-10-3

FIGURE 5-10

Anterior Cortical Opacities

Dense anterior cortical opacities can block the red reflex and interfere with visualization of the capsulorrhexis. However, even though the point of tearing is obscured in Figure 5-11, its location can be extrapolated (green lines) from the adjacent visible capsulorrhexis, the flap edge, and the line formed as the flap folds over on the intact capsule. If the flap edge were observed as indicated by the black line (a), then the point of tearing could be inferred to be at position (c), which would be consistent with the preceding section of capsulorrhexis. However, if the flap edge were visualized along the red line (b) instead of the black line (a), you could infer that the tearing point was too peripheral (d) and take appropriate measures, such as redirecting the flap more centrally or even converting to a ripping technique.

capsulorrhexis flap folded over on
surface of intact anterior capsule

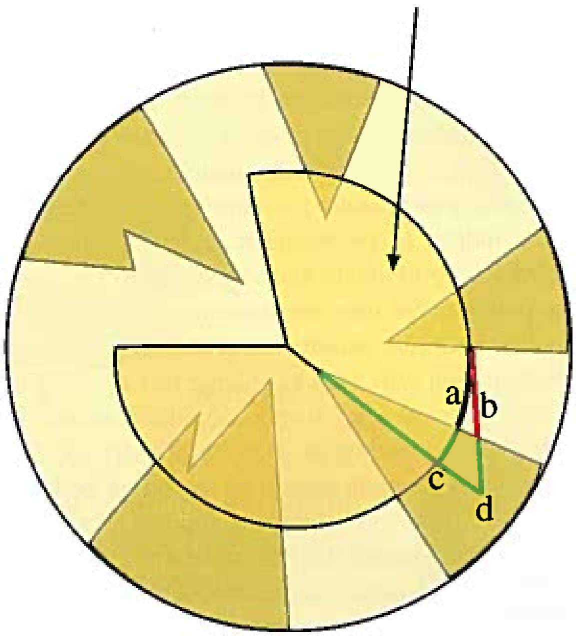


FIGURE 5-11

Capsulorrhexis Enlargement

Several surgical situations may require an enlargement of a completed CCC. A poor red reflex might induce the surgeon to initially err on the side of too small a CCC rather than too large in order to avoid a possible extension into the zonules. (A capsule stain such as ICG or Vision Blue (DORC) can help tremendously in these cases.) A small pupil may also induce a small capsulorrhexis, although in these cases the pupil should be enlarged by stretching (per Dr. Luther Fry) or iris retraction hooks. Even in otherwise routine cases, a surgeon might simply judge a CCC to be too small prior to IOL implantation, especially if the patient has pseudoexfoliation syndrome and is therefore at greater risk for postoperative contracture of the CCC (capsule phimosis). Sometimes, the CCC may be judged to be eccentric. Finally, future technologies may require enlargement. For example, Avantix (previously known as Catarex) technology, as described by Dr. Richard Kratz, promises the potential for true intracapsular cataract removal through an eccentric 1.2 mm CCC; this will provide maximum endothelial protection. However, until an injectable gel IOL material is available, the surgeon will have to enlarge this opening to utilize current IOLs.

If CCC enlargement is performed prior to phacoemulsification, the intact crystalline lens provides structural support to the capsule just as with the primary CCC. However, CCC enlargement is often performed after phaco when an improved red reflex better delineates the actual size and shape of the primary CCC. In these cases, capsule support should be maximized as much as possible by the use of viscoelastic to expand the bag and form a pseudo-nucleus (Figure 5-12-4). In addition to filling the bag with viscoelastic, further viscoelastic is instilled in the anterior chamber to flatten the anterior capsule by posteriorly displacing the capsular bag so as to help neutralize extraneous anterior zonular traction that could induce a peripheral extension (recall Figure 5-5). CCC enlargement after IOL implantation should generally be avoided, as the haptics can produce extraneous centrifugal forces on the capsular bag that may produce a peripheral extension when the intact CCC is incised to begin an enlargement.

A final aid in facilitating rhexis enlargement involves attention to the initial enlarging incision. If this incision is made normal (perpendicular) to the rhexis (point a in Figure 5-12-1), the likelihood of peripheral extension is increased because of the centrifugal force exerted by the anterior zonules (recall Figure 5-5-2). It would be difficult to convert the direction of this incision to the desired path circum-parallel to the existing CCC. In order to overcome these potential pitfalls, the initial enlarging incision should be made tangent to the CCC circle (point b), thereby initiating the tear in the appropriate direction and resisting peripheral extension. Furthermore, a critical element of CCC enlargement is the utilization of the more delicate shear technique (Figures 5-12-2 and 5-12-3) as opposed to inadvertent ripping maneuvers that would distort the delicate capsule support and lead to a higher incidence of peripheral extensions.

All of these principles can also be used to guide posterior capsulorrhexis, such as when the surgeon wishes to surround and strengthen a small rent in the posterior capsule. The only additional step would be to supplement the viscoelastic illustrated in Figure 5-12-4 with further viscoelastic posterior to the rent in order to tamponade vitreous (Figure 5-12-5), thereby reducing the chance of inadvertently inducing vitreous traction while performing the posterior capsulorrhexis.

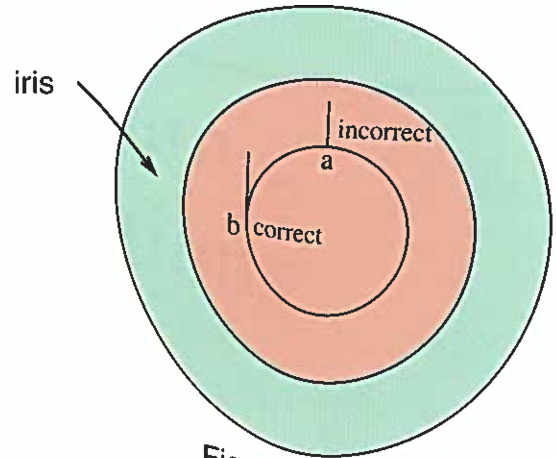


Figure 5-12-1

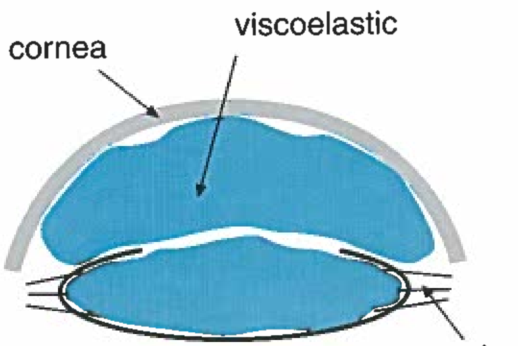


Figure 5-12-4

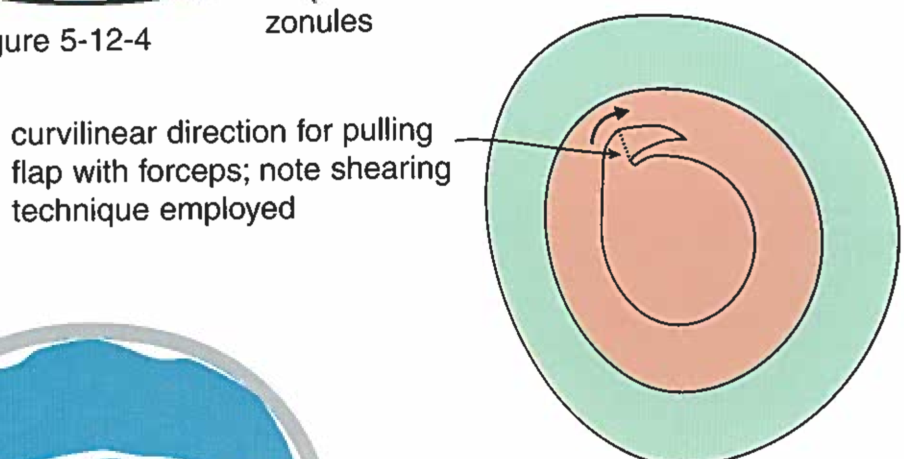


Figure 5-12-2

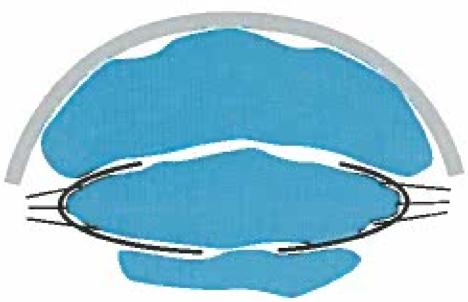


Figure 5-12-5

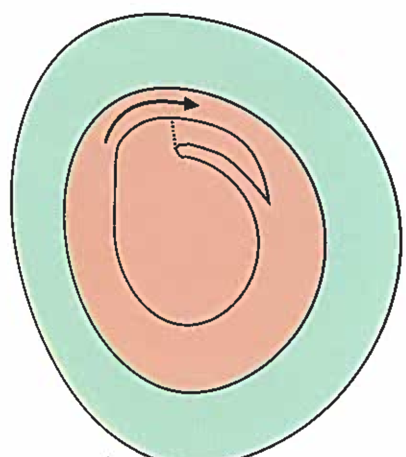


Figure 5-12-3

FIGURE 5-12