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2 Tissue Tactics

Whereas spatial tactics involve the application of pressure and resistance to control spatial volumes, tissue tactics are concerned with the application of forces to *displace, divide, and unite tissues*. For atraumatic tissue manipulations such as grasping, it is desirable for the forces to be applied over the largest area possible, as determined by anatomic constraints. For procedures that create lesions in tissues, such as sectioning, the forces should be applied over the smallest area possible.[1]

In practice it is rarely possible to apply forces in such a way that all the resultant vectors act exclusively in the desired direction. Besides these "intended vectors," surgical instruments always produce "unintended vectors" that displace or deform tissues. These side-effects can alter the direction of applied surgical forces in such a way that the result is inconsistent with the surgeon's intent.

The *effects and side-effects* of an **instrument** may be referred to as its *functional characteristics*. They determine the optimum mode of application of the instrument. In addition, every **tissue** has its own mechanical characteristics (*homogeneity*, *elasticity*, *cohesion*, etc.) which call for a specific mode of application of surgical instruments. The interaction of instrument characteristics and tissue characteristics forms the central theme of general tissue tactics. Analysis of this interaction discloses techniques for the optimum utilization of instruments in any given situation, or at least for the most satisfactory compromise if an optimum solution is not possible.

[1] The critical parameter is pressure, which for a given force is inversely proportional to area.

2.1 The Application of Mechanical Energy

Mechanical forces are vector quantities which have magnitude and direction. The amount, or magnitude, of the force that can be transmitted to tissues is limited by the "**stability**" of the instrument used. If increasing force is applied to an instrument that is not sufficiently resistant to deformation (i.e., less resistant than the tissue), the force will deform the instrument rather than exert the intended effect on the tissue, and the instrument will deviate from the desired direction. To "transmit his will to the tissue," then, the surgeon should always select the most stable instrument that anatomic conditions will permit.[2]

As a general rule, forces that are not to interfere with each other should be applied independently. They may be applied at different times ("temporal separation"),[3] or, if several vectors are applied simultaneously, their mutual interference can be minimized by applying them at right angles to one another ("spatial separation"). The **rule of vector separation** should be incorporated into instrument designs so that the actual working motion of the instrument can be separated from subsidiary motions, and these in turn from the guiding motion through tissues (Fig. 2.1).

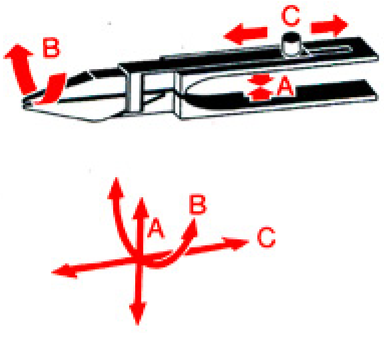

Fig. 2.1. **Rule of vector separation**, illustrated for a needleholder. The working vector *A* of the needleholder (grasping the needle) is perpendicular to the direction of needle guidance (*B*). Perpendicular to both is vector *C* (motion of the slide catch), arranged so that it will not interfere with instrument operation

2.1.1 Handles

The handle transmits forces from the fingers to the working end of the instrument, so it critically affects the precision with which the surgeon can "transmit his will to the tissue." Criteria for selecting the optimum handle for a given instrument are the type of feedback system and the spatial tactics that the surgeon wishes to employ.

With **tactile feedback**, the handle not only serves as a medium for transmitting manual forces (output) but also conveys information on tissue resistance back to the operator (input). The surgeon uses this information to regulate the forces he transmits to the tissue.

His assessment is based on an evaluation of the instrument position and the changes in that position. This process is aided by a handle design which yields unambiguous tactile and proprioceptive feedback when the instrument position is changed (Fig. 2.2).

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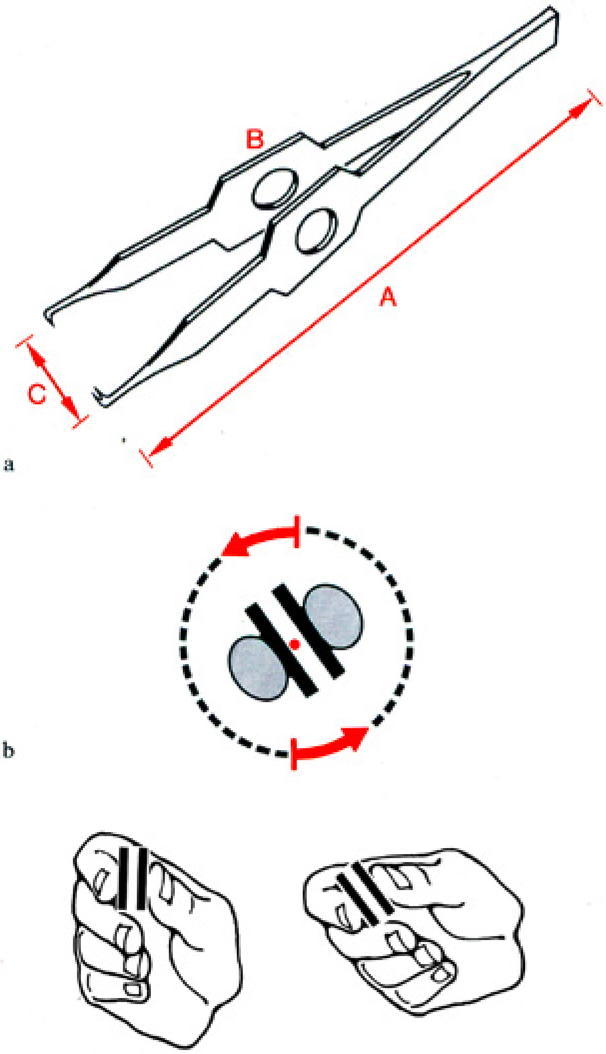
[2] This contradicts the common belief that fine instruments are superior to more heavy-duty instruments because of their smaller dimensions. In suturing, for example, a tissue-holding forceps that is too small will not offer sufficient resistance to the advancing needle and will bend; the tissue is deformed, causing the needle to deviate from the intended path.

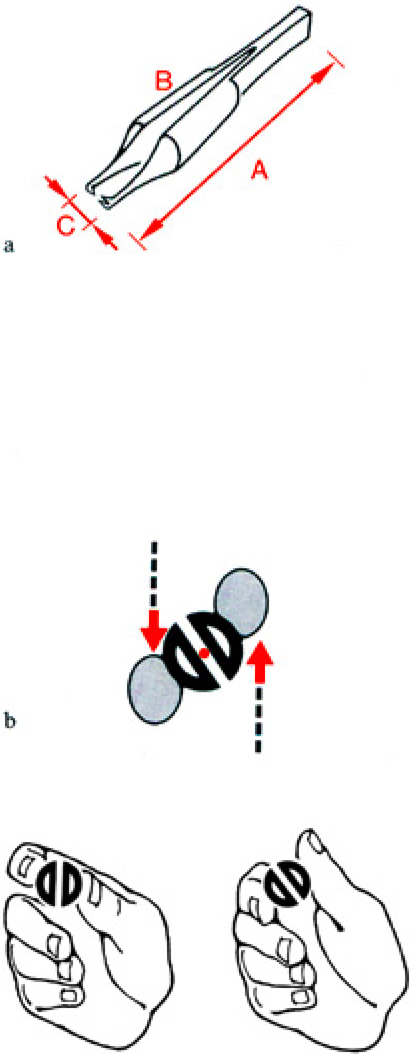
[3] Examples: 1) Separate the working and guiding motions when cutting with scissors: Do not advance or swivel the scissors while closing the blades (cutting), do not close the blades while advancing. 2) Separate the guiding and control motions in intrascleral lamellar cutting or suturing: The control motion is the lifting of the instrument tip (needle or knife tip) buried within the scleral tissue so that its position can be visualized. Do not lift while cutting, and do not advance the cutting instrument while lifting.

a



b

a



b

Fig. 2.2. **Stabilizing forceps handle**

a Tactile sensation is enhanced by placing minimal weight and tension on the fingertips.[4] This is accomplished by the following design features:

A Long handle: The weight of the instrument is borne by the metacarpus, leaving the fingertips free to guide the working end. The handle is supported at three points, making it easier to judge its position in space.

B Wide finger grips: Result in minimal finger pressure for a given force.

C Large blade opening: The increasing tension during closure of the spring handle is distributed over a long distance and therefore places minimal stress on the fingertips.

b Proprioceptive feedback is greater when motion at numerous joints is needed to redirect the handle. This is accomplished by the wide, flat grips, which require motion at the interphalangeal joints, metacarpophalangeal joints, and wrist (rotation and supination of the forearm). The schematic cross-section through the fingers and grips shows that rotation of the handle requires rotation of the fingers about the central axis of the instrument (red point)

Fig. 2.3. **Versatile forceps handle**

a The short blade length (*A*) and narrow grips (*B*) provide increased mobility. The small blade opening (*C*) puts a greater load on the fingers but facilitates visual monitoring through the microscope.

b The finger grips are rounded so that the handle can be rotated about its axis with a slight motion of the fingertips. The wrist is not moved. The schematic diagram shows that simple motions of the fingers in opposite directions are sufficient to rotate the forceps

[4] Sensitivity $= \delta J/J$ according to the Weber-Fechner law (J: Intensity of stimulus).

back to index

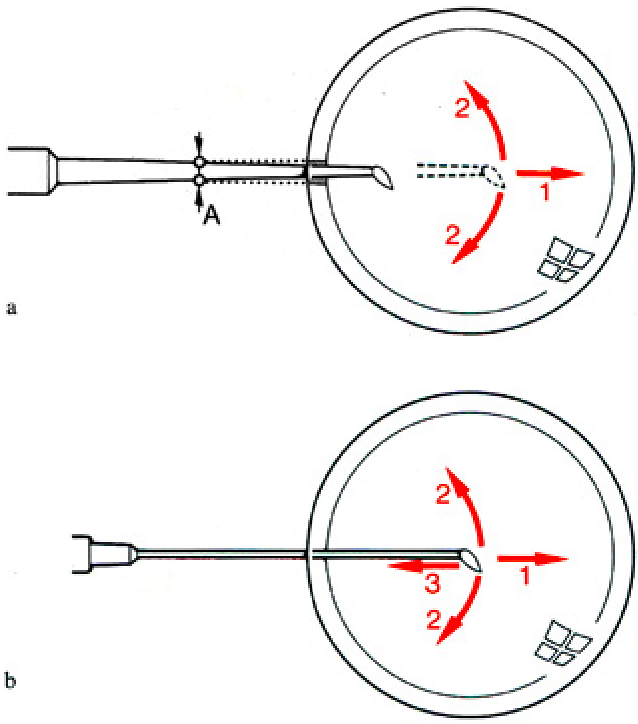


Fig. 2.4. **Handles for no-flow systems (illustrated here for a cystitome)**

a Conical handle: Water tightness improves as the knife is advanced, but withdrawal permits uncontrolled leak. Conical handles seal the wound only during insertion (*arrow 1*) and lateral swiveling movements (*arrow 2*). There is one dilemma associated with the use of conical handles: If the width of the handle just behind the blade equals that of the cutting edge (and therefore that of the incision), the instrument cannot be passed deeply into the chamber. But if the handle width equals the incision width at a site farther back on the handle (point *A* in the figure), wound leak can occur until the instrument has been inserted to that point. The problem of wound leak in this intermediate phase can be mitigated by advancing the cystitome very rapidly.

b Cylindrical handles seal the incision even as the instrument is withdrawn (*arrow 3*), provided the cross-section of the handle equals that of the blade. This places very high demands on the manufacture of the instrument, because the cross-section of the blade is difficult to define, and the handle must be custom-tooled to match it precisely

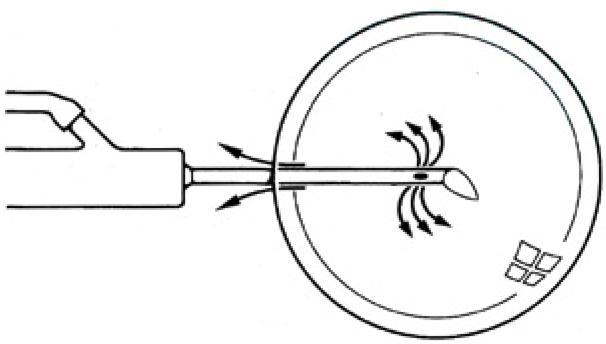


Fig. 2.5. **Infusion handle for controlled-flow systems**. The handle is hollow and serves as an infusion channel. Fine instruments have a narrow lumen. Therefore, the inflow resistance is high and a high inflow pressure is needed (pump, syringe)

Visual feedback does not rely on sensory input from the handle. Handles that can change their working direction with a minimum of motion and effort are suitable when visual feedback is employed. This design is advantageous in that the hand may rest on a support while only the fingers operate the handle. The small dimensions and short travel of the instrument facilitate monitoring in the small field of the operating microscope (Fig. 2.3).

Handles that require greater finger and wrist motion to change their position are suitable for stationary use such as fixation (Fig. 2.2). Handles that can be controlled with minimal finger motion are more versatile and facilitate guidance movements that involve direction changes.

When selecting the handle shape for a particular **space-tactical system**, it must be considered whether the handle needs to seal the access opening. A no-outflow system requires an extremely effective *seal*, and the system stands or falls with the design (and mode of guidance) of the handle. Handles with a *conical* stem produce an effective seal while they are advanced, but the slightest withdrawal will compromise the seal and allow aqueous leak (Fig. 2.4a). This problem does not exist with *cylindrical* handles, which may be freely advanced and withdrawn (Fig. 2.4b). In systems that incorporate fluid inflow (controlled-outflow systems and no-outflow systems with infusion), handles may be designed as *hollow tubes* to provide an access channel for the infusion (Fig. 2.5).

back to index

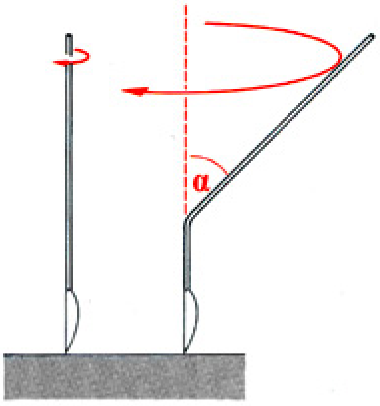


Fig. 2.6. **Guidance and working motions for simple handles.** *Left*: With a straight handle, rotation of the blade requires an identical rotation of the handle. *Right*: With an angulated handle, the blade is rotated by a swiveling motion of the handle whose amplitude depends on the angle α

Another technical criterion for the design of handles is the relation of the working motion to guidance motions. In **one-piece handles** the working and guidance motions are performed in the same direction, the amplitude of the motion depending on the angle between the handle and the working end (Fig. 2.6). In **two-piece handles** the working and guidance motions act in different directions. While both parts of the instrument are guided in the same direction, the working motion consists of two countermovements about a connecting joint or axis. *Force transmission* from the handle to the working end (jaws) is a matter of leverage and depends on the relative lengths of the handle and jaws. The *precision* of the force transmission depends on the quality of the joint. Thus, the shorter the jaw length in relation to the handle, the higher the transmitted force and the greater the necessary stability of the joint (Fig. 2.7). If larger forces are applied to the instrument than its construction provides for, its components will bend, and the jaws will

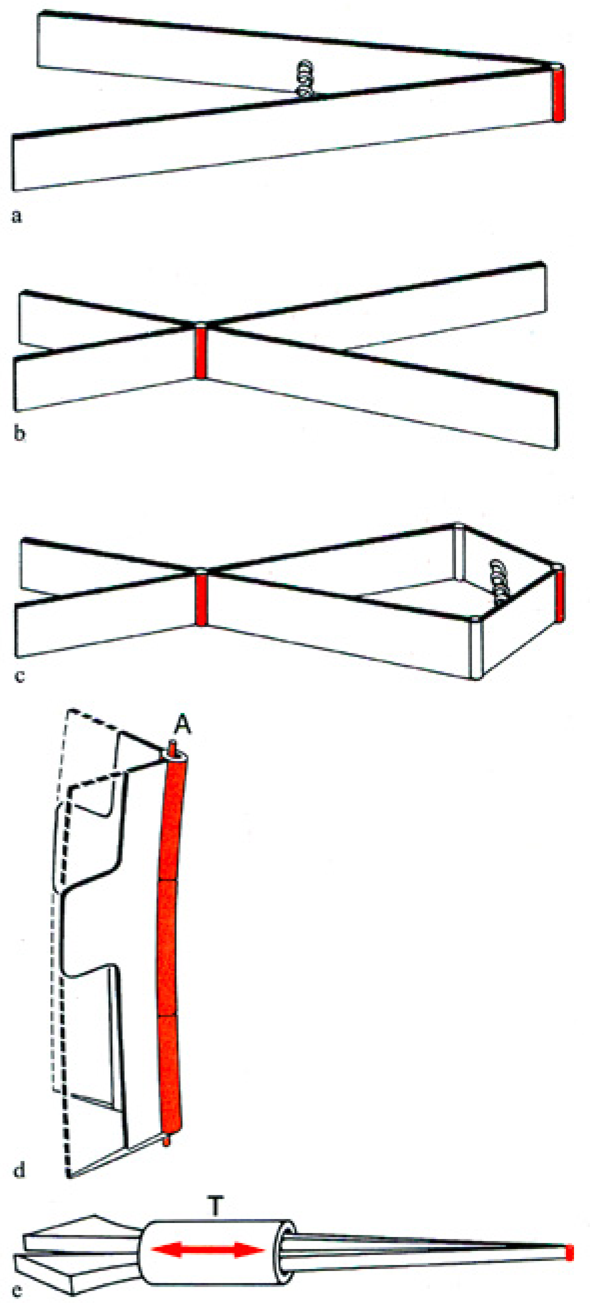


Fig. 2.7. **Force transmission and stabilization in two-piece handles**

a Simple forceps handle: The working part and handle are identical. Force transmitted from the fingers to the jaws is not mediated by a stabilizing joint. The precision of closure depends entirely on the stable and precise construction of the blades.

b Scissors handle: The joint (screw) is very short in relation to the blades, so precision depends largely on precise finger movements.

c Spring handle: An extra joint stabilizes blade closure and makes it more precise.

d Hinged handle: The joint length is maximal and equals that of the entire handle. The length of the force-transmitting lever arm does not depend on the total length of the handle. The spring tension necessary for opening is produced by a slight flexure of the joint (*A*).

e Tube handle: Very fine blades are enclosed in a stabilizing guide tube (*T*), which is slid forward to close the jaws

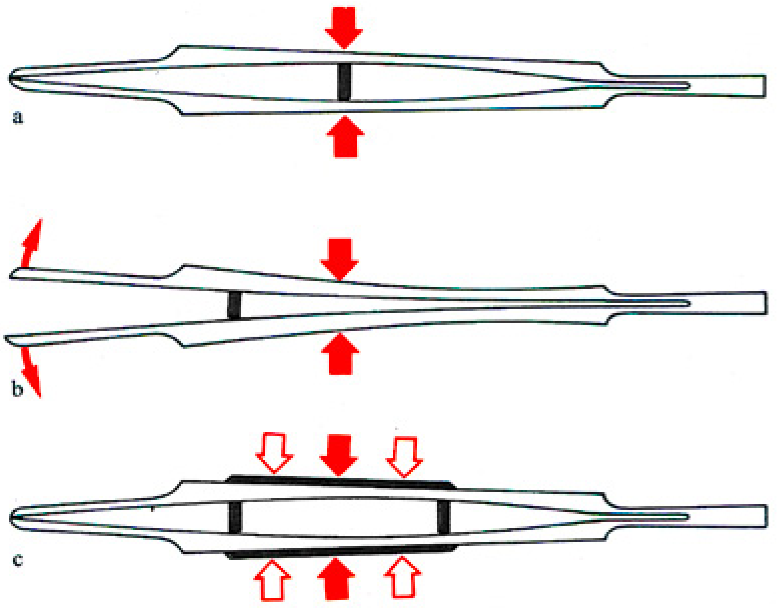


Fig. 2.8. **Regulation of force by stops.** Stops limit the pressure that can be applied to the instrument handle.

a To work properly, the stops must be placed directly below the point of finger contact.

b If the handle is squeezed behind the stops, the jaws will separate instead of close.

c When two stop pins are provided and the intervening handle is reinforced, finger pressure may be applied over a larger area

not appose correctly.[5] Precision instruments should therefore be fitted with *stops* which limit the force that can be applied (Fig. 2.8).

Besides considerations of force transmission, anatomic and geometric factors are relevant to selecting an appropriate instrument design. For operations in the interior of the eye, it is advantageous to use instruments whose working axis can be placed very close to the access opening. This will ensure a minimum instrument cross-section in the opening when tissues are cut or grasped, allowing the instrument to be used freely through an aperture of minimal size (Fig. 2.9).

[5] This problem can be reduced by using a more rigid steel for the jaws than for the flexible spring handles. Precision instruments of this kind are recognized by the soldered joint between the handle and working end. (Note that the melting point of the solder limits the sterilization temperature).

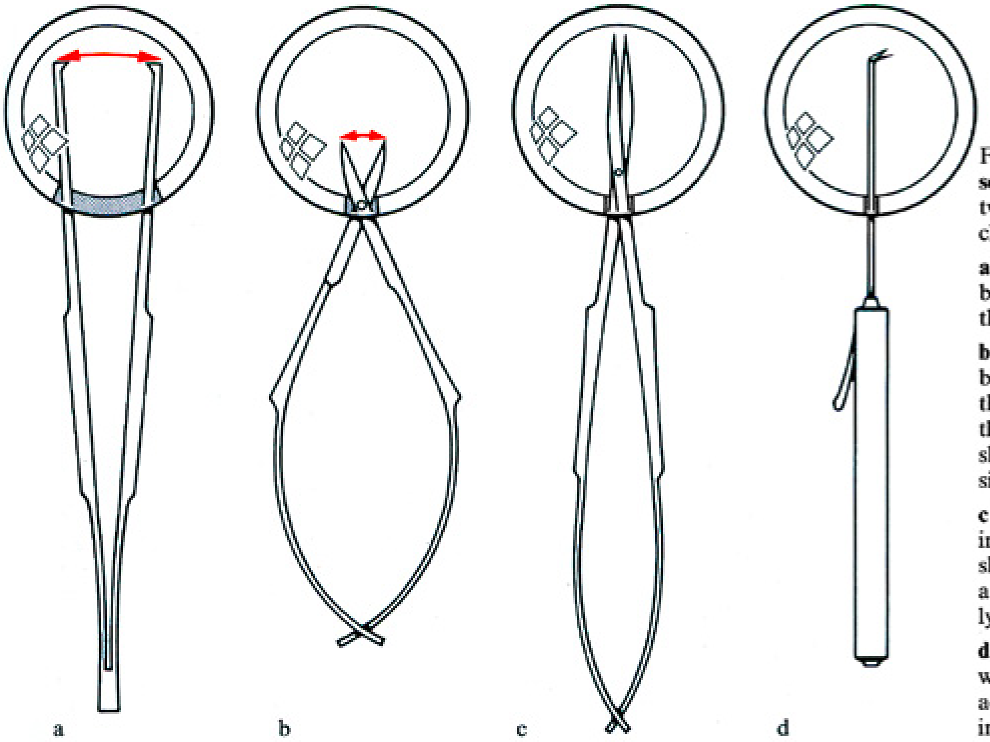


Fig. 2.9. **Geometric factors relating to the selection of blade length,** illustrated for two-piece instruments used in the anterior chamber.

a Simple forceps handle. The maximum blade opening is limited by the width of the chamber incision.

b In articulated handles, the blades may be opened without regard for the size of the incision if the joint is held exactly at the entrance. Spring-handled scissors with short blades may be used close to the incision.

c Scissors with long blades can work deep in the chamber. In the type of scissors shown here there is very little separation at the incision owing to the slender, slightly curved blades.

d Instruments with tubular handles always have a constant cross-section in the access opening, regardless of the depth of insertion

back to index

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Motorized Handles

Handles in which the working motion is motor-driven convey no tactile impression of tissue resistance, so the surgeon must rely entirely on visual feedback. As there is no risk of interaction between the working and guidance motions, motorized handles are appropriate for high-precision work in which the surgeon must concentrate entirely on guiding the instrument.

Rotating knives (trephines, circular knives) have "infinite" blade excursions which offer the advantage of consistent cutting quality owing to their long, uniform cutting action. The main risk is that the rotating blade will snag unsectioned tissue fibers and cause the tearing of tissues remote from the intended site of action.

This danger is avoided by the short excursions of **oscillating knives**. The amplitude of the blade motion is limited by the design, making it safe to operate the instrument at extremely high speeds. It must be considered, however, that individual blade movements are invisible at high speeds (Fig. 2.10), so the cutting process cannot be *monitored* by watching the blade itself but only by observing its effect on the tissue.

2.1.2 Grasping

Grasping serves to transmit guidance motions to a substrate. The *guidance motion* may be an active movement performed to **mobilize** the substrate (e.g., for transposition or removal), or it may be a stationary action intended to **immobilize** the substrate (e.g., for tissue fixation during cutting or suturing).[6] In order for force transmission to occur, a frictional resistance must be created between the instrument and substrate. The necessary level of this resistance depends on the forces that must be overcome by the guidance motion.

Frictional resistance is determined by:
- the *forces* exerted on the substrate;
- the *area of blade contact*;
- the *angle* at which the forces act on the substrate.

To preserve structures during the grasping of *tissues,* high pressure should be avoided whenever possible and the necessary friction produced by increasing the area of blade contact or selecting a more favorable angle of attack. When grasping a *solid object* such as a needle, however, the grasping area is limited and the angle of attack is predetermined, so friction is produced mainly by applying a large gripping force.

Spatulas

Solid Spatulas

With a solid spatula, force is transmitted directly from the handle to the area of tissue contact. This ensures a high precision in grasping.

Simple spatulas are suitable for forward and lateral pivoting move-

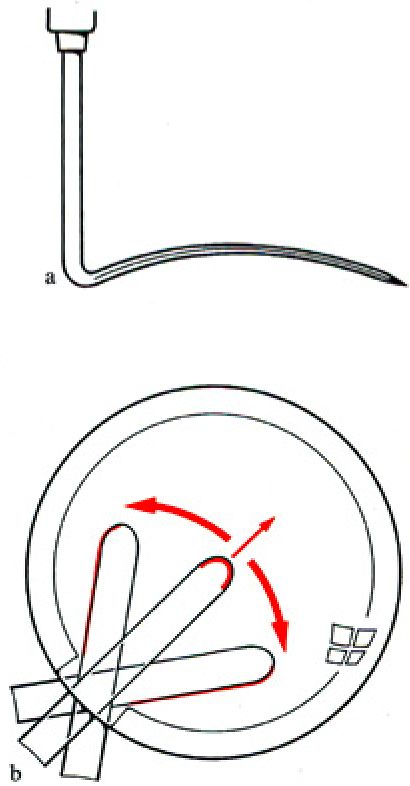


Fig. 2.11. **Simple spatula**

a The simple spatula has a uniform cross-section over its entire length, so it can be guided in a way that keeps the incision watertight during all manipulations (see Fig. 5.18D for suitable type of incision). Long blades are slightly curved to conform to the curved intraocular surfaces.

b The basic working motions of the simple spatula are thrusting (small working surface, high pressure), pivoting (larger working surface, lower pressure), elevation and depression (largest surface). The lateral working surfaces are shown in *red*

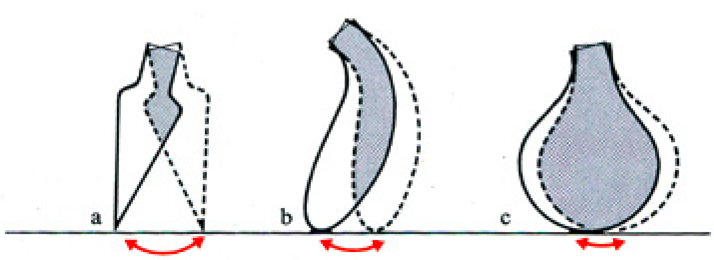


Fig. 2.10. **Oscillating blades.** Individual blade movements are invisible at high frequencies, and only the overlapping portion can be seen (*gray*). Note that the tip of the blade in contact with the tissue is invisible in **a** and **b** but can be seen in **c**

[6] Versatile handles are preferred for active manipulations, stable handles for fixation (see Fig. 2.2).

back to index

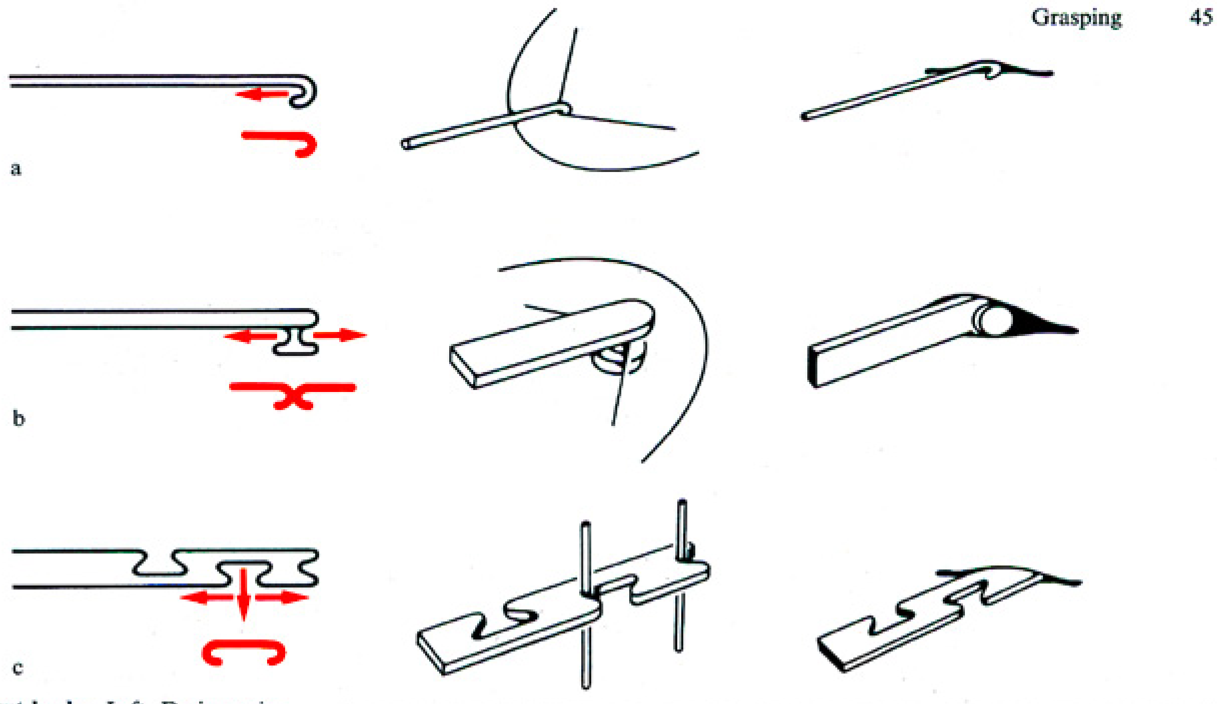


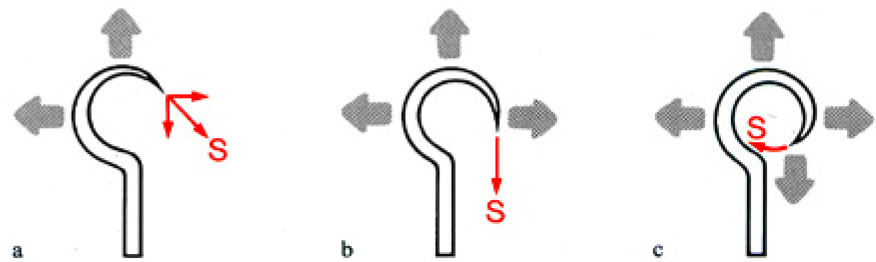
Fig. 2.12. **Blunt hooks.** *Left*: Design principle. *Center*: Possible applications in tissue. *Right*: Introduction through incisions.

a Simple hook for applying traction to tissue. The hook is turned sideways for insertion through an incision.

b Collar-button probe: Consists basically of an infinite number of blunt hooks in a centrifugal arrangement, can push or pull in any direction. The probe is inserted sideways so it will not catch the wound edge.

c Flat spatula with notches: Consists basically of several hooks pointing in opposite directions, can pull or push strands and posts in any direction; slips smoothly through small incisions

ments (Fig. 2.11). **Hooks** are used for snaring and pulling tissues. *Blunt hooks* can be moved freely in all directions without traumatizing adjacent tissues but can be used only to grasp and apply traction to free edges (e.g., the pupillary border or implant margins) (Fig. 2.12). *Sharp hooks* can also engage tissue surfaces but may traumatize surrounding tissues. Hence a special technique is required for inserting and removing sharp hooks through incisions (Fig. 2.13).



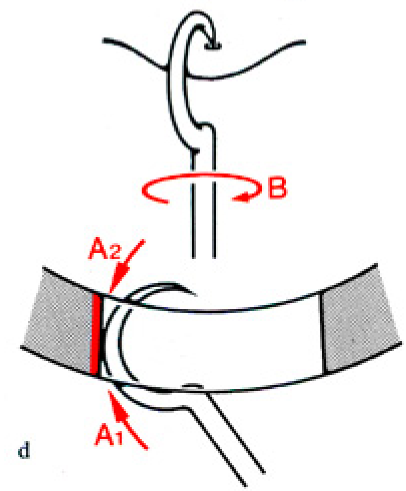


Fig. 2.13. **Sharp hooks.** The hooks are sharply pointed in the direction of the working motion. If the guidance direction coincides with the working motion, the hook may cause inadvertent damage when moved within the eye. The hook behaves as a sharp instrument (*S*) in some directions (*red arrows*) and as a blunt instrument in others (*gray arrows*).

a A hook with less than a 270° curve engages tissue when pulled backward or swiveled laterally (toward the hook opening). It is blunt only when pushed straight forward or swiveled in a direction away from its opening.

b A hook with a 270° curve is sharp only when pulled straight backward. It is blunt in all other directions.

c A hook with more than a 270° curve can be safely maneuvered in all directions. It is sharp only when rotated to engage tissue prominences (e.g., iris trabeculae).

d For passage into or out of an incision, a sharp hook is turned sideways with its back surface pressed against one side of the wound (*A*). Having traversed the incision, the hook is rotated into the working position (*B*)

back to index

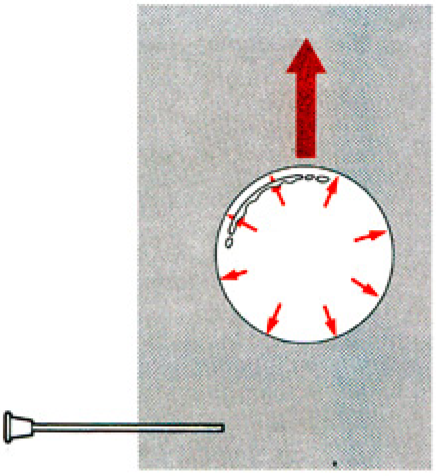


Fig. 2.14. **Bullous spatula.** A bubble exerts force as an instrument without manipulation by the operator. It exerts centrifugal forces on the environment by virtue of the surface tension and internal pressure that give the bubble its spherical shape. In addition, gravitational effects produce upward-directed forces in light bubbles and downward-directed forces in heavy bubbles

Bubbles as "Spatulas"

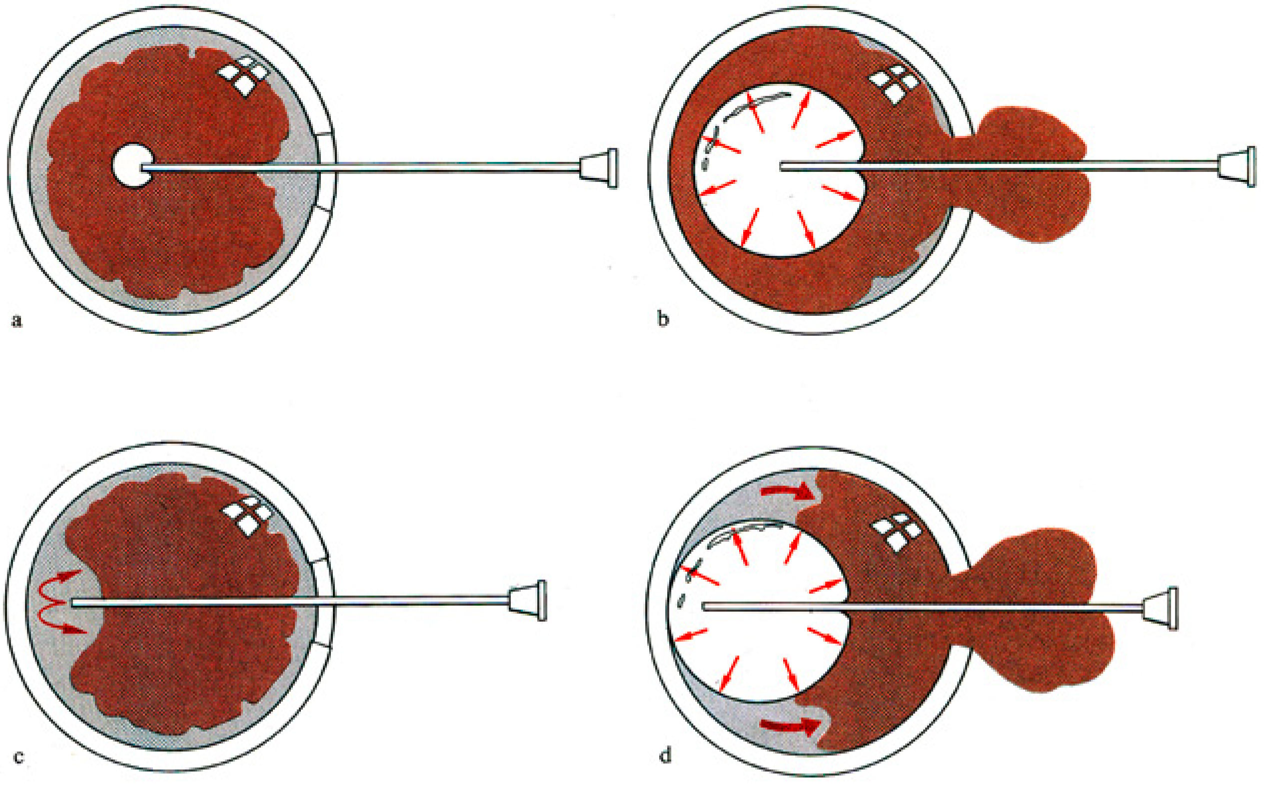
Bullous "spatulas" can transmit forces to tissue in two ways: their surface tension can exert *centrifugal* forces, and their buoyancy can exert *vertical* forces (Fig. 2.14). These forces can be used to impose a spherical shape on surrounding tissues or to force tissues upward or downward.

Bullous spatulas can be introduced through openings of minimal size but, once in the chamber, can attain a considerable volume. This discrepancy can be utilized to apply forces over a broad area (Fig. 2.15).

The forces are independent of the actions of the surgeon, who can directly control only the *size* of the "spatula" and indirectly controls its *position*. But this very independence can be utilized to maintain the effect of the spatula after its placement and to change its site of action.

The positional dependence of the effect compels the patient to maintain a certain position for as long as the bubble is in the eye. This requirement can be moderated somewhat by embedding the bubble in a highly viscous material to restrict its mobility (Fig. 2.16).

The injection technique is the same as described earlier in connection with spatial tactics (see Figs. 1.33–1.35).



2.15

back to index

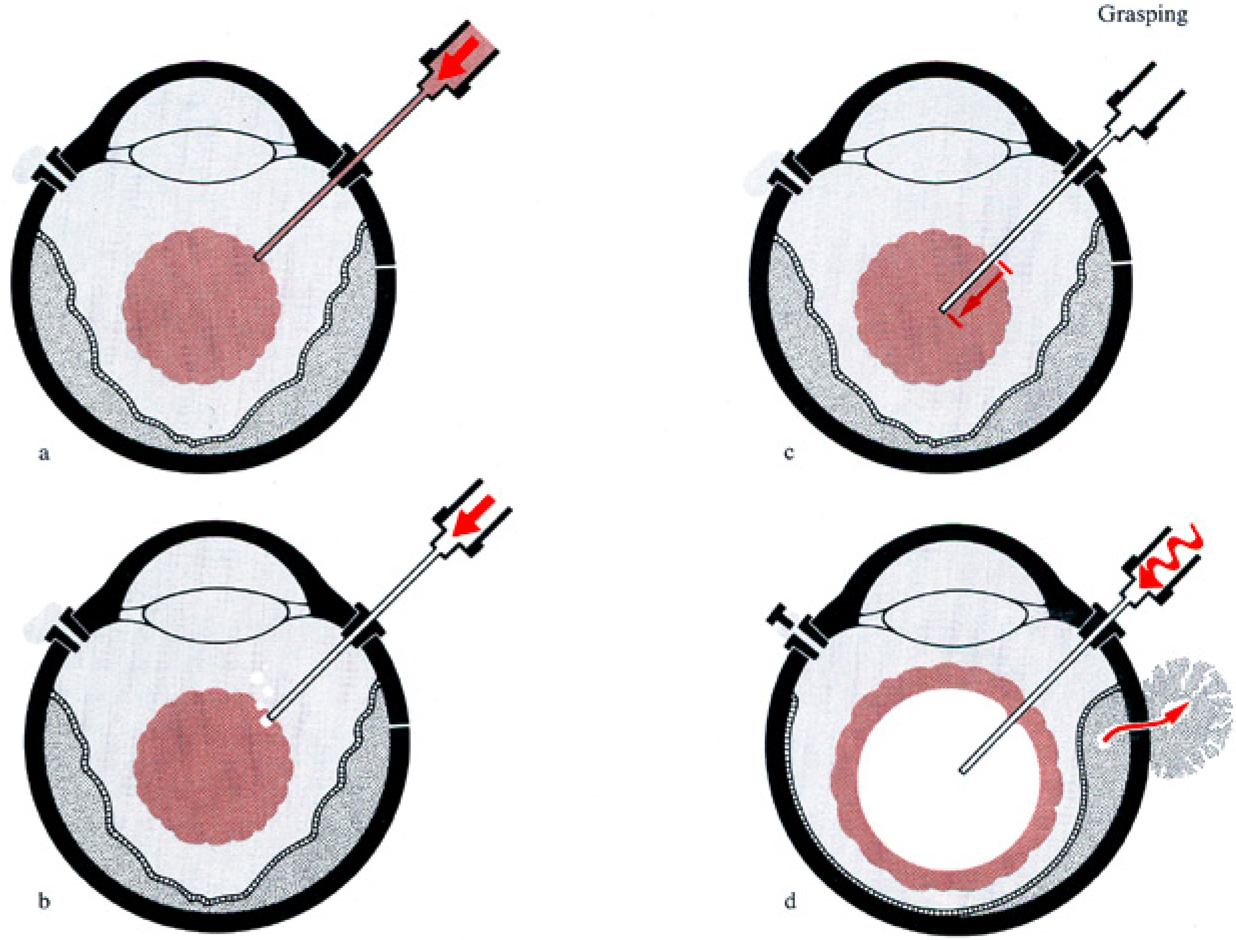


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Fig. 2.15. **Air bubble as a mobilizing instrument (for expelling viscoelastic material from the anterior chamber)**

a, b Unsuccessful attempt using improper technique. **c, d** Correct technique.

a Air injected directly into the viscoelastic material produces a viscoelastic balloon.

b If one then attempts to remove the material by enlarging the bubble, only a portion is expelled; the rest is pressed against the opposite chamber angle.

c The expulsion is first prepared by creating a watery (homogeneous) compartment. Watery fluid is injected behind the viscous material to create a nonviscous space on the opposite side.

d Expulsion is then accomplished by injecting air into the watery compartment. The air bubble forces the viscoelastic material out of the chamber.

Note: Control of the expulsion is aided by maintaining a low outflow resistance for the viscoelastic material (by opening the wound edges as in Fig. 2.24). If the resistance is too high, the chamber pressure will rise, and side-effects may occur. This pressure rise can be detected by noting that enlargement of the bubble is insufficient relative to the volume of air injected

Fig. 2.16. **"Spherical spatula": viscoelastic balloon produced by injecting gas into a viscoelastic mass (here: To reduce and stabilize a detached retina)**

a Preparation of the viscoelastic shell: Viscoelastic material is injected into the vitrectomized cavity.

b Unsuccessful attempt to inflate the balloon: If the cannula is not repositioned after injecting the viscoelastic material, and gas is injected simply by exchanging syringes, gas bubbles will form at the interface between the viscous substance and watery fluid. In this nonhomogeneous milieu the gas bubbles will follow the path of least resistance and escape into the watery milieu.

c Correct technique for inflating the balloon: Before gas is injected, the cannula is advanced into a homogeneous milieu by positioning its tip at the center of the viscoelastic mass.

d The cannula having been repositioned, the viscoelastic mass is now inflated to produce an absorbable intraocular balloon

back to index

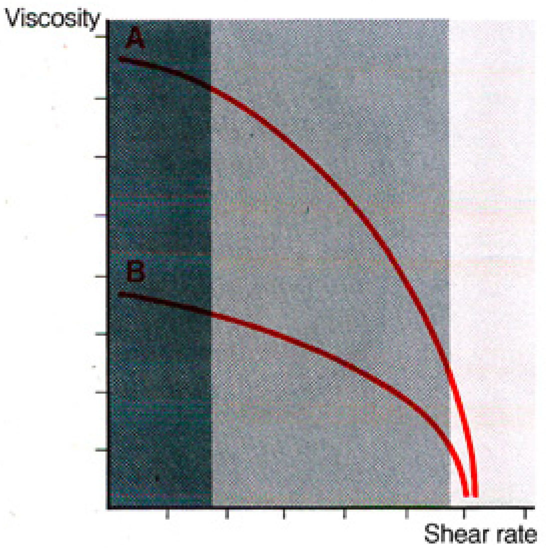

Fig. 2.17. **Suitability of various viscoelastic materials for use as a spatula, i.e., for viscostabilization and viscomobilization.** The maximum viscosity of the material (i.e., the initial viscosity at a low shear rate) determines its stabilizing effect and thus its efficacy as a "permanent spatula" (*dark gray* zone) The medium viscosity (viscosity at a medium shear rate) determines the suitability of the material for mobilization and thus its efficacy as a "soft spatula" (*medium gray*). The minimum viscosity (viscosity at a high shear rate) determines injectability through thin cannulas (*light gray*). The high-molecular substance *A* makes a more effective spatula than the low-molecular substance *B*. Both have comparable injectability (see Fig. 1.18)

Viscoelastic Materials as Spatulas

Viscoelastic spatulas, like bullous spatulas, can apply forces atraumatically over a large area even when introduced through small openings. But they differ from bullous spatulas in that their effect is not position-dependent (provided the specific gravity of the viscoelastic substance equals that of the aqueous).[7] They differ from solid spatulas in that the link between surgeon and tissue is influenced by the viscosity of the material; control is indirect and consequently less precise.

Viscoelastic materials may be characterized as "**soft permanent spatulas.**" As they are injected, they displace tissues and act as *soft* spatulas to produce a nontraumatizing *visco-mobilization*. After the injection they function as *permanent* spatulas by holding the tissues in place and providing a long-term *immobilization* ("visco-stabilization").

Their high internal flow resistance and elasticity enable viscoelastic spatulas to transmit forces to their surroundings (Fig. 2.17). The *effect* depends on the ratio of the internal resistance of the spatula to external resistances. This ratio determines whether the viscoelastic spatula, when introduced, will displace the surrounding tissue or will be displaced by it (Fig. 2.18).

The viscoelastic material may block its own flow by damming back toward the cannula, causing subsequently injected material to spread along paths of least resistance. Thus, the surgeon cannot predict the effect of the viscoelastic spatula based on the position of the cannula or the force of the injection. As a general rule, however, the best effect is obtained when there is minimal distance between the cannula opening and the target site, for this reduces the area in which there may be unintended blockage or deviation of the flow.

Besides injecting close to the target site, **control** is effected by **modifying flow resistances** about the target site, the goal being to maintain a lower resistance in the intended flow direction than in all other directions. This principle is illustrated in Figs. 2.19–2.22. It will be noted

[7] The viscoelastic spatula cannot exert its effect as long as a bubble can. Although the bubble will diminish in size with absorption, it retains its essential properties (i.e., it remains impermeable and continues to displace in accordance with its specific gravity). It will exert its effect as long as it retains a sufficient size. In the viscoelastic spatula, on the other hand, dilution of the material in the eye alters its viscosity and elasticity, and its effect diminishes even if it continues to occupy a sufficiently large volume.

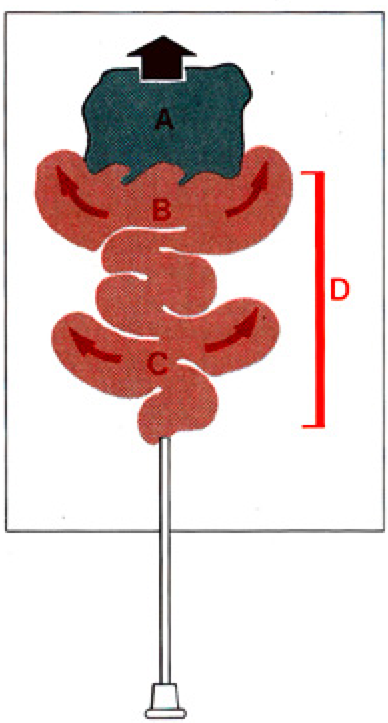

Fig. 2.18. **Viscoelastic spatula**. The relationship between the external resistance of the tissue particle to displacement (friction and inertia) and the internal resistance of the material (viscosity) determines whether the viscoelastic material will displace the particle (*A*) or flow around it (*B*). For a given viscosity, the distance (*D*) between the cannula outlet and the target will determine whether the material evades (*C*) or acts on the particle

back to index

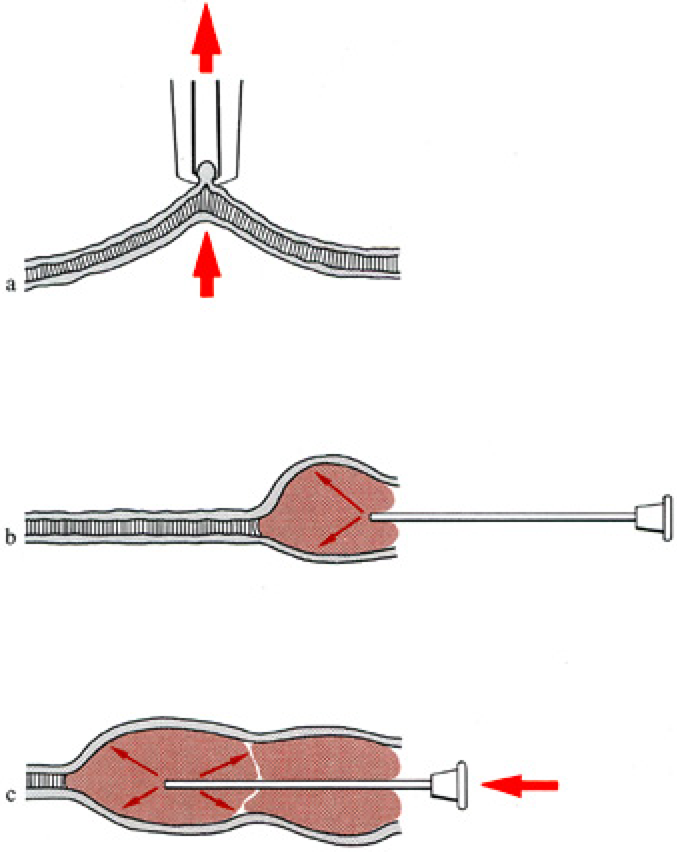

Fig. 2.19. **Separation of adherent tissue layers with a viscoelastic spatula**. Technique for cases where the resistance to separation of the layers is less than the reflux resistance of the viscoelastic material.

a Indication: Separation of thin, delicate layers that are too mobile and compliant to be pulled apart with grasping instruments.[8]

b The intermediate layer is located with the cannula tip, and the viscoelastic material is injected into the interspace.

c Because the reflux resistance is greater than the resistance to separation, the injected material is forced into the interspace and bluntly separates the layers.

Note: The cannula tip is pushed forward as injection proceeds to keep the distance between outlet and working area short (i.e. to minimize the distance D in Fig. 2.18)

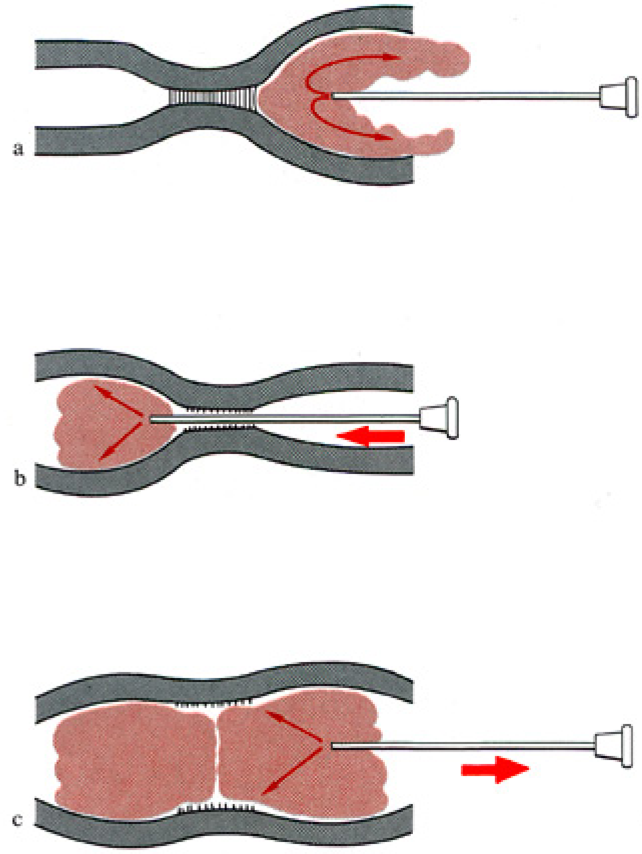

Fig. 2.20. **Separation of adherent tissue layers with a viscoelastic spatula.** Technique for cases where the resistance to separation of the layers is greater than the reflux resistance of viscoelastic material.

a Indication: Separation of firm adhesions between tough tissue layers.[9] Because the reflux resistance is lower, the flow of viscoelastic material is deflected away from the adhesion.

b It is necessary first to sever the adhesions with the tip of the cannula ("solid spatula") before injecting the material.

c The injection is continued while the cannula is withdrawn. Here the viscoelastic spatula does not effect the separation but functions as a permanent spatula to maintain the dehiscence created with the solid instrument

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[8] Examples: Separation of coagulated blood from the anterior surface of the iris; separation of a preretinal membrane from a detached retina.

[9] Examples: Separation of the ciliary body from the scleral spur (cyclodialysis, see Fig. 6.1); clearing of firm synechiae (see Fig. 7.30).

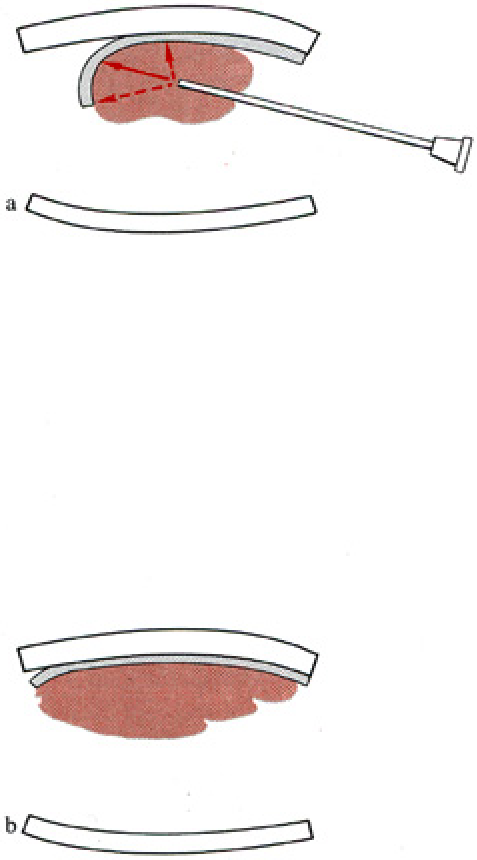

Fig. 2.21. **Approximation of two separate tissue layers with a viscoelastic spatula.** Technique for cases where the resistance to approximation of the layers is less than the reflux resistance.

a A fine membrane is approximated to another tissue layer.[10] The injection is directed obliquely to produce vector components perpendicular to the tissue surface (to effect the approximation) and also parallel to it (to advance the approximation). The viscoelastic material functions here as a soft spatula.

b The injected material keeps the membrane approximated to the substrate, functioning now as a permanent spatula

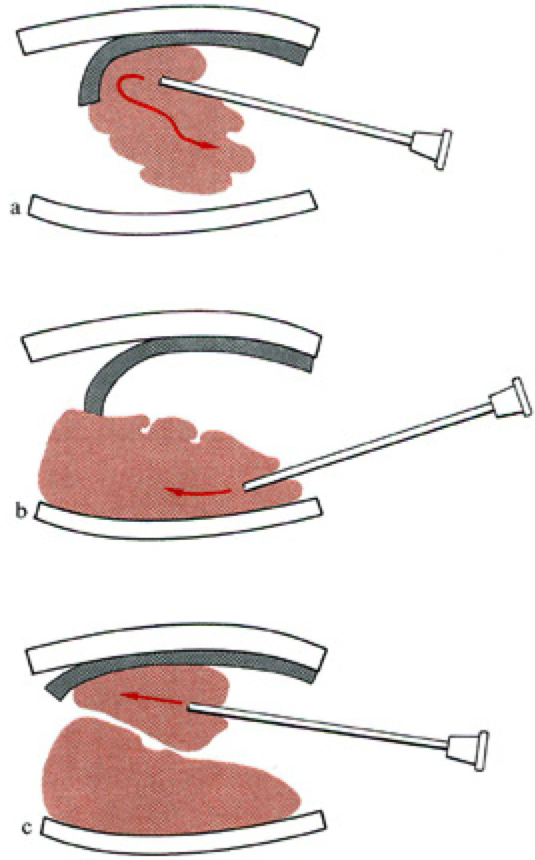

Fig. 2.22. **Approximation of two separate tissue layers with a viscoelastic spatula.** Technique for cases where the resistance to approximation is greater than the reflux resistance.

a When an attempt is made to press the firm tissue layer against a substrate, the flow of material is deflected onto a path of lesser resistance, and reflux occurs.

b The initial step, therefore, is to block that path with viscoelastic material.

c In a second step the "soft spatula" is injected to approximate the tissue layers (analogous to Fig. 2.21 a)

that the viscoelastic material itself can provide resistance to flow in undesired directions.[11] This effect can be enhanced by the use of higher-viscosity materials (substance A in Fig. 2.17).

If material with sufficiently high viscosity is not available, resistance may be decreased in the desired direction by using a solid instrument (e.g., the cannula itself) to clear any obstructions along the intended path of flow. The viscoelastic material is then injected and will function as a permanent spatula to maintain the dehiscence (Fig. 2.20).

[10] Examples: Replacement of a detached Descemet membrane; reapposition of a torn lens capsule to the hyaloid membrane (see Fig. 8.108).

[11] Gas bubbles may be used to increase resistance *above* the target site (see Fig. 7.35 b).

back to index

The Use of Watery Fluids for Mobilization and Grasping

Watery fluids can exert forces through pressure gradients, and their control consists accordingly in the regulation of pressures and resistances. The operator may employ positive pressure as a means of mobilizing tissues (irrigation) or negative pressure as a means of grasping tissues (aspiration).

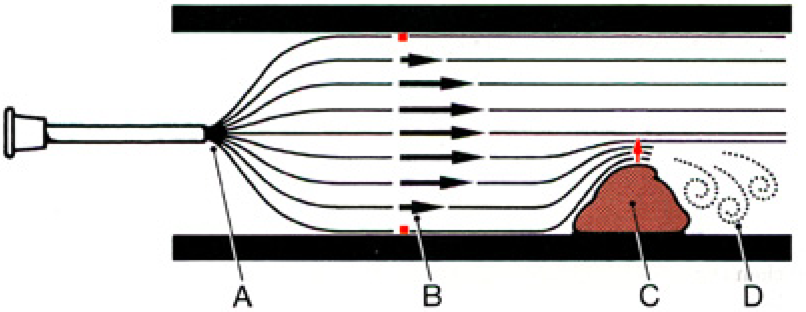

Fig. 2.23. **Basic hydrodynamics of irrigation.** At sites of narrowing in the flow channel, as over a particle, the flow velocity increases (i.e., the streamlines move closer together).

A The channel is narrowest in the irrigation cannula, so the flow velocity is maximal at the cannula outlet (see Fig. 1.15a).

B Velocity distribution in laminar flow: The flow velocity is always zero at the surface of solid bodies. The velocity increases with distance from the surface (*arrows*).

C Vectors perpendicular to the surface occur when the channel is narrowed by an obstacle. As flow velocity increases, pressure falls (Bernoulli's law), causing a lifting force to be exerted on a particle in the flow. The magnitude of this lifting force depends on the square of the flow velocity.

D Eddy currents can form behind the obstacle. The intensity of these currents depends basically on the shape of the obstacle and the flow velocity but cannot be predicted in a given case

Irrigation

Irrigation can be used both to mobilize tissues and to transport them. In **irrigation for mobilization**, the irrigating stream dislodges tissue particles from surfaces to which they are adherent. Hence the fluid stream must produce *force vectors directed away from the tissue surfaces*. Such vectors are produced by the negative pressure that arises at sites of narrowing as a result of asymmetric flow. The magnitude of this effect, called *dynamic lift*,[12] depends on the flow velocity around the particle to be mobilized (Fig. 2.23C). Irrigation for mobilization, then, must employ a high-velocity fluid stream. The flow velocity is highest at the cannula outlet (Fig. 2.23A), so the cannula tip is placed as close as possible to the particle to be mobilized.[13] The optimum flow direction is not squarely onto the particle, but parallel to the surface to which the particle is adherent.

Irrigation for transport of tissue material suspended in the stream is actually a simple fluid exchange analogous to *space-tactical fluid systems*.[14] Thus, the tip of the cannula may remain close to the access opening. Low velocities are sufficient and also optimal because they are easier to control. This procedure differs from space-tactical systems in that the *flow resistances* in irrigation are not geared toward considerations of pressure but toward the size of the particles to be transported. In practical terms this means that flow paths must be kept wide enough to eliminate friction between the particles and tissue surface. The *control* of transport irrigation, then, involves regulating the outflow resistance in such a way that this *resistance remains high while the particle is being transported* through the chamber in order to keep the chamber volume large. However, *when the particle comes to trasverse the incision*, a *low outflow resistance* is needed since the outflow path from the chamber must be as wide as possible (Fig. 2.24).[15] Transport irrigation, then, employs a low-velocity fluid stream and a well-coordinated sequence of increased and reduced outflow resistances.

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[12] Dynamic lift is the net upward force produced by asymmetric flow velocities around an object (such as an aircraft wing).
[13] This contrasts with fluid applications in spatial tactics, where the cannula tip is placed at the access opening.
[14] In fluid exchange, the particle and fluid have the same velocities, whereas in mobilization the fluid velocity is greater.
[15] This makes it necessary to provide an inflow capacity commensurate with the size of the particles to be transported.

back to index

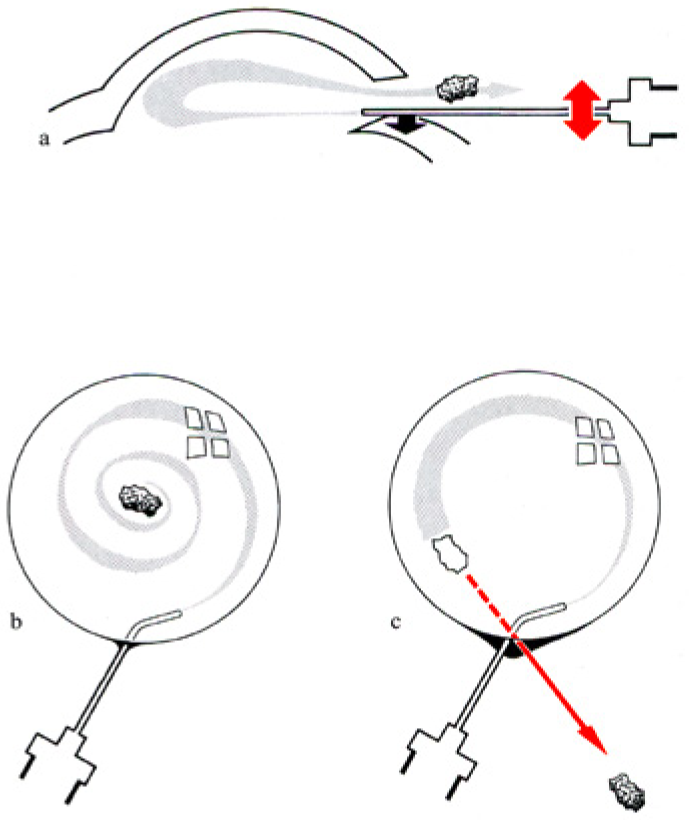


Fig. 2.24. **Control of irrigation for transport: removal of material from the anterior chamber**

a Inflow pressure is controlled by the pressure on the syringe plunger, outflow resistance by the degree of wound opening, i.e., by raising or lowering the cannula (see also Fig. 1.14).

b Mobilization of the particle inside the chamber: With a high outflow resistance, the anterior chamber will remain deep, and the irrigating stream will mobilize the particle and keep it flowing within the chamber. If the injection rate is too high, it will produce eddy currents instead of a uniform stream.

c Removal of the particle from the chamber: When the outflow resistance is lowered, the fluid stream and entrained particle will exit the chamber. The incision is not opened at the moment the particle is adjacent to it but somewhat earlier, when the motion vector of the particle (the tangent to its circular path of motion) is directed toward the incision

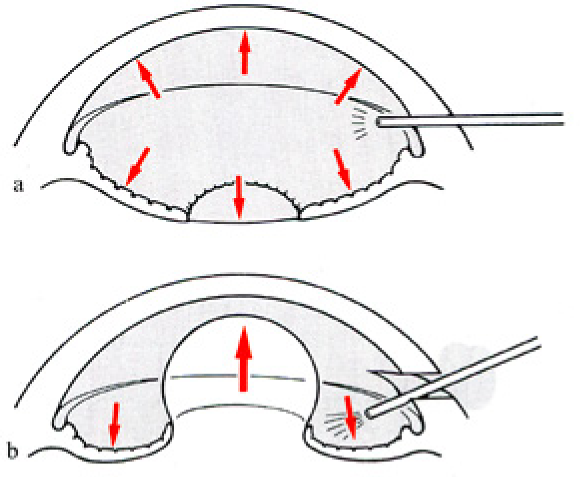


Fig. 2.25. **Control of irrigation: Spatial tactics**

a If the outflow resistance during irrigation is high, rising pressure in the anterior chamber can push the diaphragm inward and expand the chamber volume.

b If the outflow resistance is low, the chamber pressure does not rise as fluid is injected. The chamber contents are redistributed, but the chamber volume does not increase. If a portion of the diaphragm (iris) is pressed backward, another portion (anterior hyaloid) is extruded forward. If this occurs while the cannula tip is at the center of the chamber (and not at the access opening), the protruding part (e.g. vitreous) is at risk for injury

Aspiration
Aspiration allows for a more selective manipulation than irrigation. The *site* of the critical pressure gradient is strictly localized to the cannula opening, which is positioned precisely where the action of the pressure gradient is required. The magnitude of the pressure difference is influenced by the resistance at the cannula inlet. This resistance provides the distinction between aspiration by occlusion and aspiration by flow.

Aspiration by occlusion is a *mobilizing procedure*. The inlet of the cannula is completely occluded by the material to be mobilized, raising the *resistance* to infinity and causing a cessation of flow. The pressure gradient at the cannula tip is maximal and approaches the difference between the chamber pressure and the terminal pressure (Fig. 2.26a).[16]

Aspiration by occlusion is controlled by regulating both of these pressures. The *adhesion* of the particle to the cannula can be *increased*, and the particle "gripped" more tightly, either by increasing the chamber pressure (e.g., raising the infusion pressure) or by lowering the terminal pressure (i.e., increasing the suction).[17]

To *decrease the adhesion* of the particle to the cannula for the purpose of release, the opposite procedure is followed: either the terminal pressure is increased above the level of the chamber pressure, or the chamber pressure is reduced below the terminal pressure (by lowering the infusion pressure).

Once occlusion has occurred, fluid can no longer flow through the cannula, and there is no need for volume replacement by infusion.[18] Occlusion of the cannula also eliminates the danger of inadvertent tissue aspiration.

The *safety strategy* for aspiration by occlusion requires the suction to remain turned off while the tip of the cannula is placed against the particle to be grasped. Once it is certain that the particle occludes the cannula, the suction may be turned on. Note: Partial occlusion is no occlusion, and any aspirating maneuver will become aspiration in flow.

Aspiration in Flow. Aspiration in flow is a *transport procedure*. The inlet of the cannula is open, the *resistance low*, and the pressure difference correspondingly small (Fig. 2.26b). Flow through the cannula is continuous, and fluid infusion is mandatory for volume replacement. Aspiration in flow, like transport irrigation, is basically a *space-tactical fluid system* with the difference that the suction tip is placed selectively at a particular target.

Because the inlet of the cannula is open, anything in front of the opening will be aspirated. This increases the potential for inadvertent aspiration. This danger increases with the flow velocity, since eddy currents and dynamic lift can draw tissues from apparently safe regions into the area of the suction tip. The safety strategy for aspiration in flow requires low flow velocities, therefore.

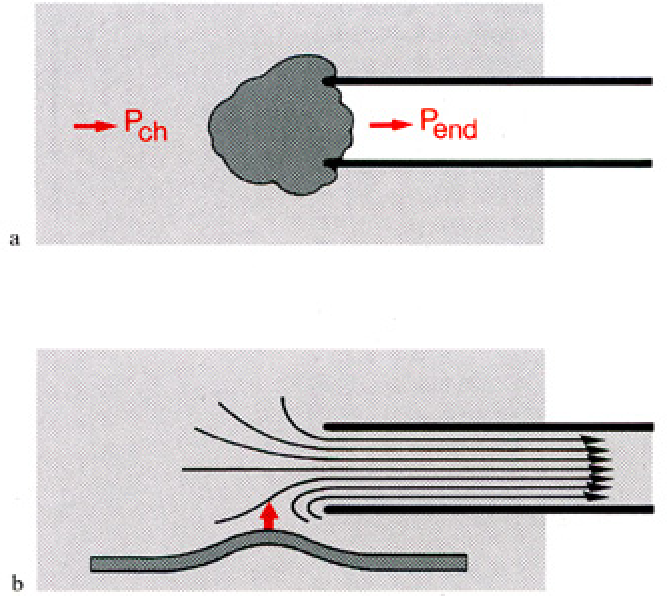


Fig. 2.26. **Methods of aspiration**

a Aspiration by occlusion: With total blockage of the aspirating channel, the resistance at the cannula inlet becomes infinitely high. The pressure difference at the inlet (P_{ch} vs. P_{end}) is maximal.

b Aspiration in flow: The cannula inlet is unobstructed, and the resistance is finite. The pressure difference at the inlet is the difference between the chamber pressure P_{ch} and the exit pressure P_{exit} and therefore is very small (see Fig. 1.2). At high flow rates, dynamic lift can occur at sites with asymmetric flow, drawing movable objects (here: a membrane) toward the inlet. This can occur even when the cannula is parallel to the surface of the object

[16] Note: The level of the chamber pressure depends on how effectively the access opening is sealed around the cannula. If the outflow resistance next to the cannula is infinitely high (see Fig. 1.4a), the chamber pressure will equal the initial pressure. If the outflow resistance is zero, the chamber pressure will equal atmospheric (see Fig. 1.6).

[17] For example, if the chamber pressure is zero (due to a low outflow resistance to the external atmosphere, see Fig. 1.6), a strong suction is required. Conversely, if the terminal pressure is zero (e.g., in a cannula that communicates with the open air), a high infusion pressure is required.

[18] Compensatory fluid infusion is necessary only if there are other outflow sites besides the occluded cannula (see Fig. 1.5c).

back to index

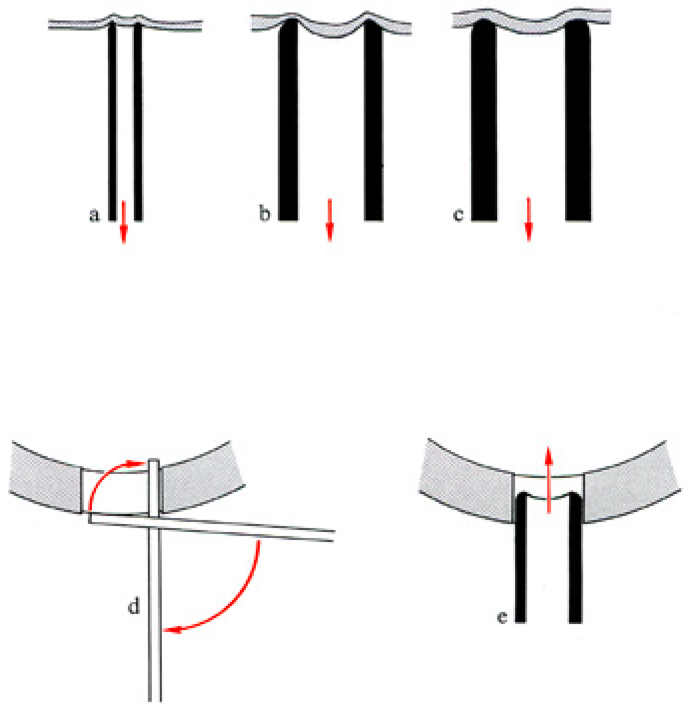


Fig. 2.27. **Configurations of cannula openings**. *Top*: Cannula tips in cross-section. *Bottom*: Guidance maneuvers for passing cannulas through incisions. All the cannulas can be used for irrigation, but only cannula **c** is suitable for aspiration by occlusion.

a Thin cannula: Thin cannulas also have thin walls, which act as a sharp instrument when pressed against tissue. This may occur during aspiration or during forward-directed guidance motions.

b Thick-walled cannula with a rounded outer edge: The cannula acts as a blunt instrument during guidance motions, but its inner edge behaves as a sharp instrument during aspiration.

c Thick-walled cannula with rounded inner and outer edges: The cannula acts as a blunt instrument even during aspiration.

d If the cannula has a sharp outer edge (e.g., cannula **a**), it should be passed side-first through incisions, as illustrated. This swiveling maneuver requires a relatively broad wound opening.

e Cannulas with a rounded outer edge (**b** and **c**) may be introduced point-first, so they can negotiate even narrow wounds

Cannulas for the Application of "Fluid Instruments"

The *shape of the tip* of the cannula is critical when the instrument is used for tissue tactics (unlike cannulas for volume maintenance, where only the cross-section is significant; see Fig. 1.12). The tip design is less critical for **irrigating cannulas** since all tissues are forced away from the opening. But in **aspirating cannulas**, which draw tissues toward the opening, even the slightest irregularity at the tip can increase the risk of inadvertent tissue lesions.[19] The tip design is especially critical in aspiration by occlusion (Fig. 2.27), where the integrity of the system depends on the *shape* of the rim (Fig. 2.29a). The *direction* of the opening determines the angle of application to the tissue and influences how the particle will reorient itself when occlusion is established (Fig. 2.28). If the material is to be transported through the lumen of the cannula, it is advantageous to have a lumen of larger caliber than the aspirating port (Fig. 2.29b).

[19] This is of lesser importance for tissues that are deliberately aspirated (e.g., lens cortex, vitreous), but there is always a risk of aspirating tissues that should remain in the eye and whose damage could compromise the surgical goal (e.g., lens capsule, retina).

back to index

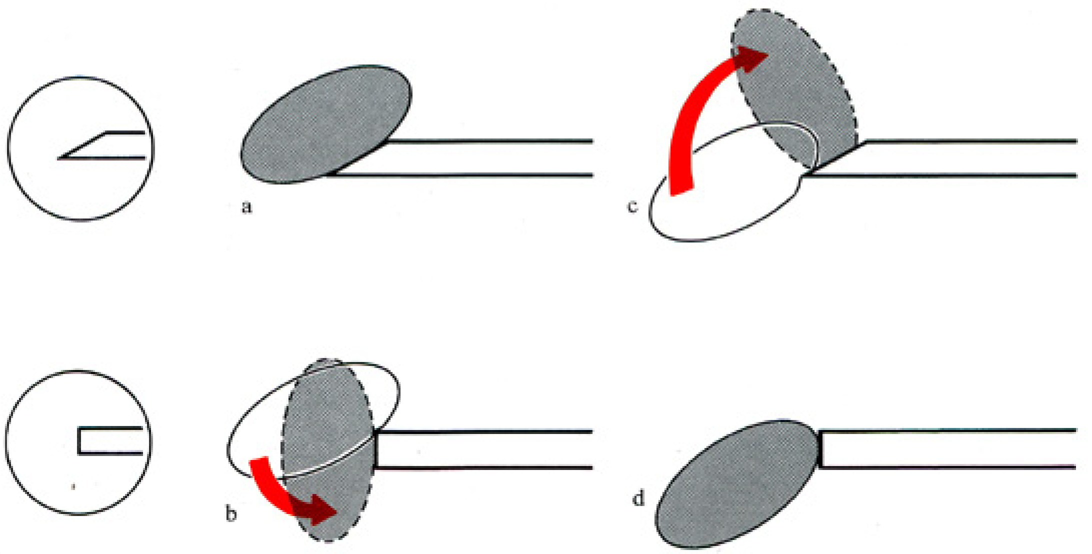


Fig. 2.28. **Effect of cannula bevel on grasping**
a, c Oblique bevel (opening faces laterally).
b, d Flat bevel (opening faces forward).
In **a** and **d** the cannula tip apposes flush to the tissue surface; in **b** and **c** it does not.

a An aspirating cannula whose oblique bevel matches the orientation angle of the particle surface (so the surfaces of the particle and cannula opening are parallel) can grasp the particle without changing its position.

b A flat-beveled cannula applied at the same site does not appose flush to the particle, so the latter must rotate into an orientation where the surfaces are parallel. This may be associated with unintended tissue contacts about the particle.

c An obliquely beveled cannula produces a similar rotation when applied to a vertical surface.

d The particle in **c** would not rotate if grasped at the same site with a flat-beveled cannula

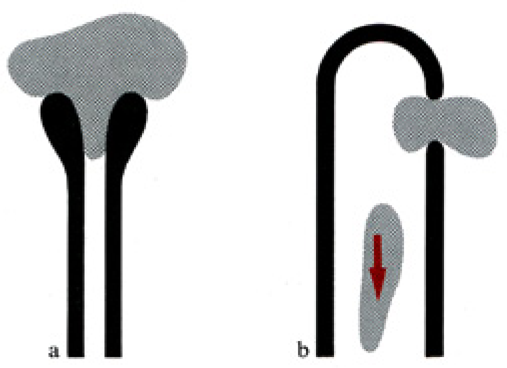


Fig. 2.29. **Relationship of cannula opening and lumen in the grasping or aspiration of tissue**

a Cannula for grasping only: The inner surface of the opening has a conical shape so that particles of various sizes can occlude the inlet, but its narrow lumen prevents the material from being aspirated through the cannula.

b Cannula for both grasping and transport: Here the lumen is larger than the opening so that particles encounter little resistance after passing through the inlet

back to index

Forceps

Nontoothed Forceps

Forceps without teeth must have a sufficiently large grasping surface in order to produce sufficient friction. Because they place relatively little pressure on the substrate, they can grasp and hold delicate tissues and materials without damaging them.

In forceps with a **variable grasping surface** (Fig. 2.30), the *flexibility* of the blades determines whether increased pressure with the fingers will enlarge the contact area or raise the grasping pressure. If the blades are very rigid, the pressure increases considerably before the grasping surface can enlarge sufficiently, and the tissue is crushed. But if the blades are flexible, the pressure remains low, and little friction develops despite the large grasping surface.[20]

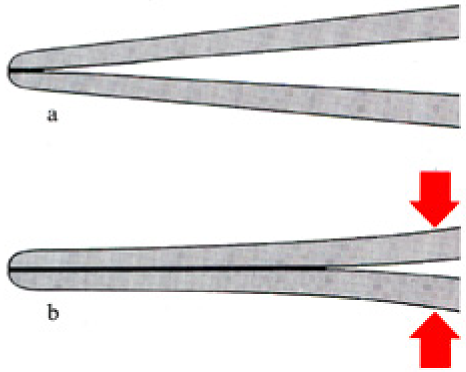


Fig. 2.30. **Plane forceps with undefined grasping surface**. As increasing force is applied to the blades, the grasping area increases (**b**), but the jaw pressure (= force per unit area) does not rise accordingly. Thus, the efficacy of the instrument relies on the contact area (and friction) that is established between the blades and the object grasped

In forceps with a **predefined grasping surface** (Fig. 2.31), the blade pressure is determined by the construction. If the pressure on the blades is too low, only the tips will meet; if too high, the jaws will separate. *Pressure-regulating devices* are necessary, therefore (see Fig. 2.8).[21]

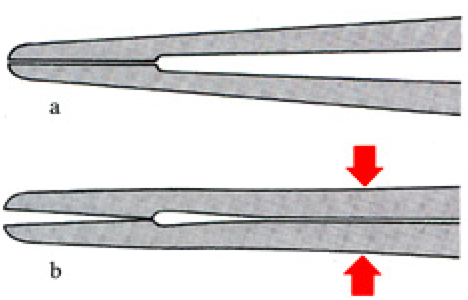


Fig. 2.31. **Plane forceps with predefined grasping surface**

a The grasping surfaces meet only when a specific blade pressure is applied.

b If greater pressure is applied, the grasping surfaces begin to separate and, in contrast to Fig. 2.30b, the effective grasping area is diminished

Serration on the inside of the jaws increases the grasping surface of the forceps and changes its angle of attack on the tissue. This provides increased friction without altering the dimensions of the forceps (Fig. 2.32).

However, serration is effective only in soft material whose surface can conform to the shape of the ridges. Serration produces the opposite effect in hard material, because it reduces the contact area and weakens the grasping effect (Fig. 2.32c). The *pattern of the serrations* determines the direction in which maximum resistance is obtained, i.e., the direction in which traction can be exerted with optimum effect (Fig. 2.33).

In *miniforceps* grooving also provides greater stability for a given cross-section of the closed instrument (Fig. 2.34).

The *ring forceps*, equivalent in principle to a circular serration, can exert traction in all directions (Fig. 2.35). The same principle is applied in *spoon forceps*, which add cuplike covers to the ring-shaped blades (Fig. 2.36).

[20] Function is tested by a load test with material of known weight and surface roughness.

[21] Function is tested by visual inspection of the jaws as digital pressure is increased.

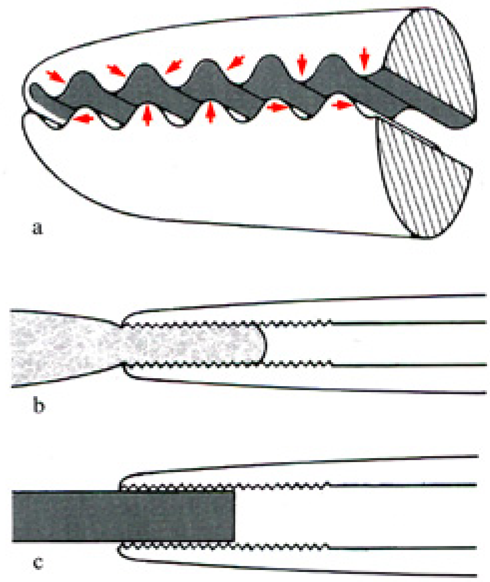


Fig. 2.32. **The principle of serration**

a Serration increases the contact area and changes the angles of attack at the substrate.

b This principle is effective on nonrigid material into which the serrations can "bite."

c On rigid material, only the tops of the serrations meet the substrate, so the contact area is actually reduced, and the varying angles of attack have no effect

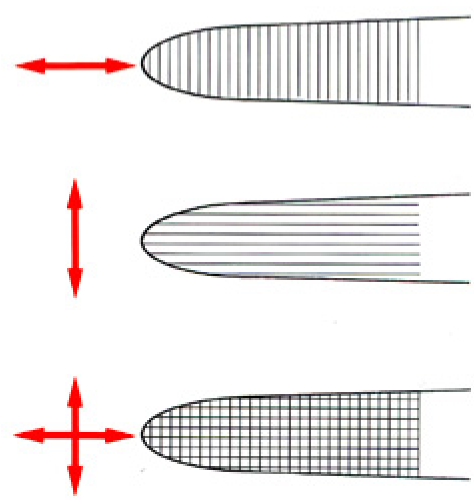


Fig. 2.33. **Directions in which serrations are most effective.** The ability to exert traction depends on the direction of the serrations. Cross-serrated jaws resist traction along the axis of the handle (*top*), while longitudinal serrations resist transverse traction (*center*). Criss-cross serrations can permit traction in all directions (*bottom*)

back to index

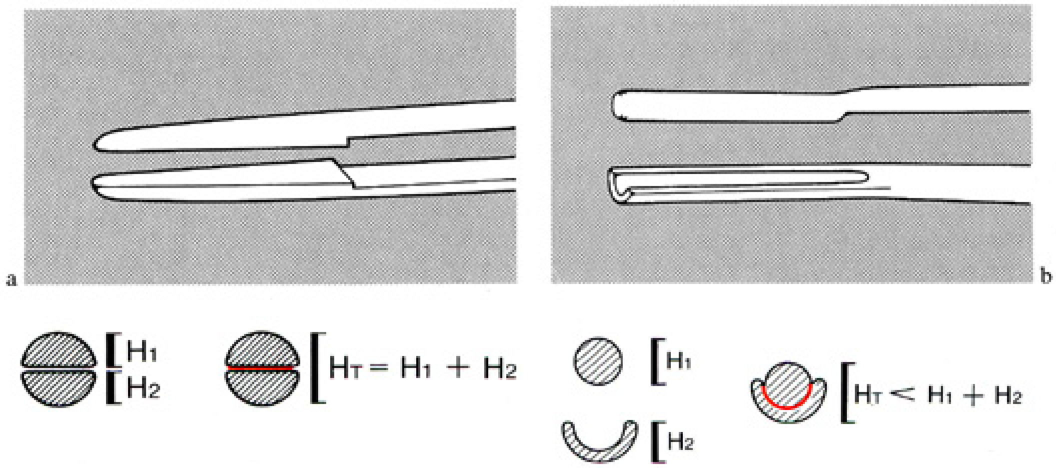


Fig. 2.34

a Miniforceps with smooth jaws: The stability of an individual blade is determined by its height *H*. The total height of the closed tip (H_T) equals the sum of the heights of the individual blades $H_1 + H_2$. The grasping surface (*red*) is related to the diameter.

b Miniforceps with a single longitudinal groove: One blade is trough-shaped, the other cylindrical. Since the blades intermesh, the total height of the closed tip (H_T) is less than the sum of the blade heights. This can give greater stability than a forceps with smooth jaws (**a**) without increasing the height. The grasping surface is greater than in **a**, and the angles of attack at the substrate are variable

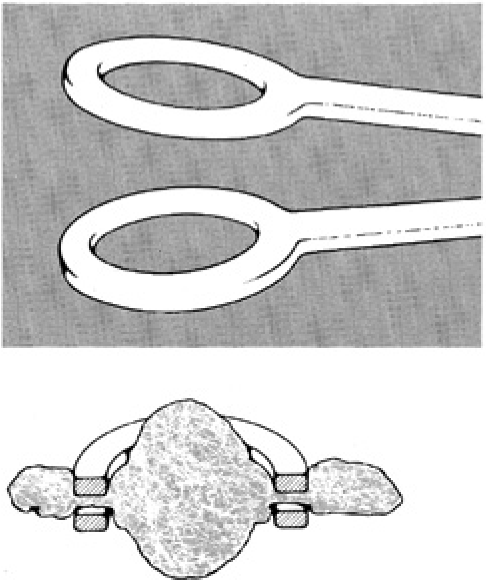


Fig. 2.35. **Ring forceps for soft material.** The material encompassed by the ring blades has a larger cross-section than the material compressed between the jaws. This keeps the tissue from shifting and thus permits traction in all directions. The small cross-section of the instrument allows passage through very narrow openings

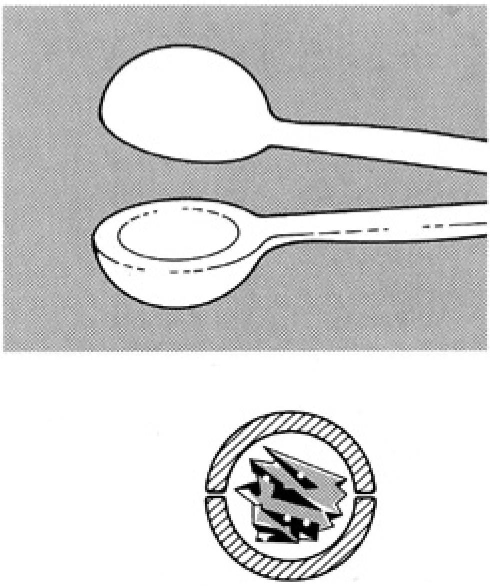
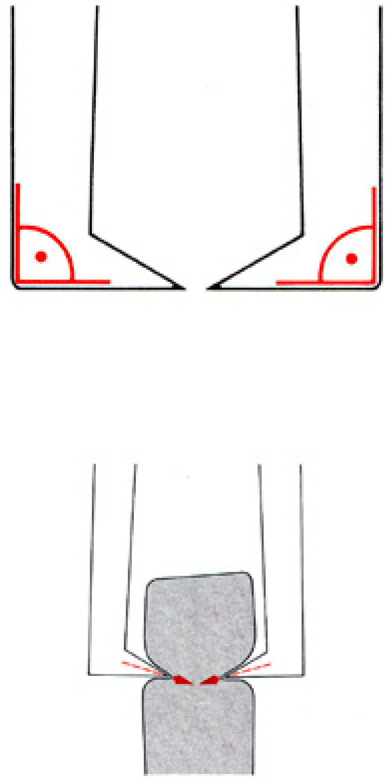


Fig. 2.36. **Spoon forceps for rigid material.** The grasping properties are similar to those of ring forceps, but the smooth outer surface protects surrounding tissues when manipulating particles with sharp edges. The cross-section is larger than that of ring forceps, so a relatively large access opening is needed for insertion into the eye

Fig. 2.37. **Straight teeth**

a In forceps with straight teeth (set at a 90° angle), the grasping vectors are directed inward.

b The vectors allow the forceps to grasp material lying *between* the blades



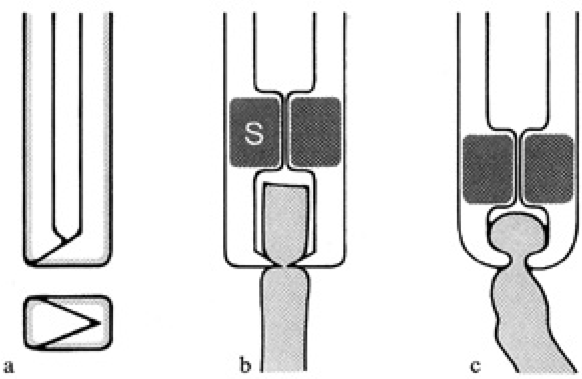
2.37 a b

Fig. 2.38. **Straight-tooth forceps designs**

a Forceps with straight teeth can be engineered so that their outer surface is completely smooth when the jaws are closed.

b For tough material such as sclera or cornea, the teeth must be sharp enough to penetrate the tissue.

c For soft material such as iris or conjunctiva, blunt nonlacerating teeth may be used.
Stops (*S*) prevent tissue trauma



2.38 a b c

Toothed Forceps

Toothed forceps have a very small grasping area defined by the configuration of the teeth. This makes them suitable for precise "pinpoint" grasping. They exert a high pressure, however, and may damage delicate tissues.

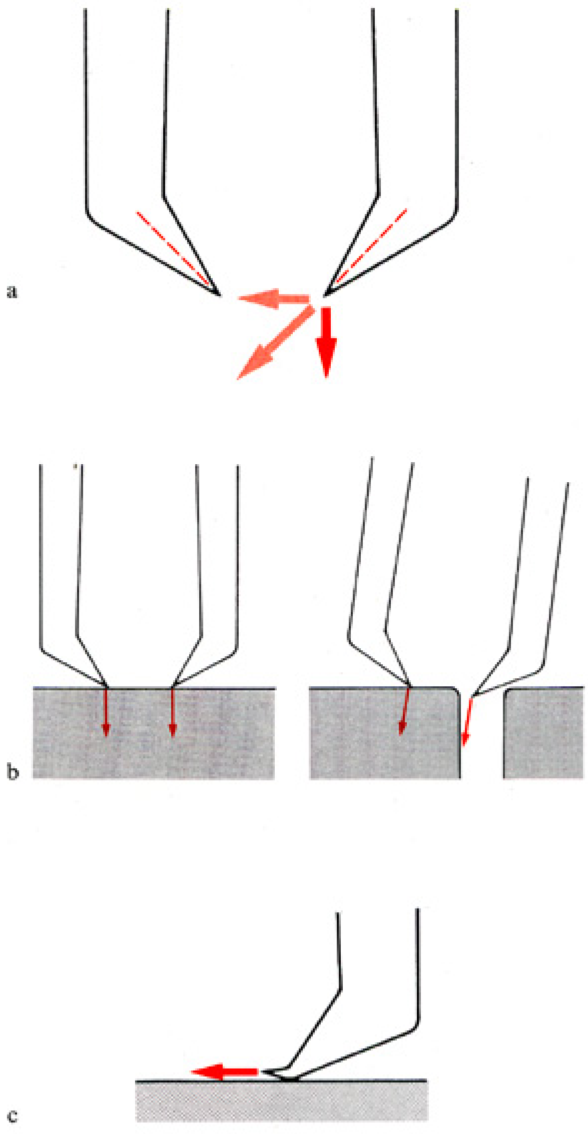
Toothed forceps produce their grasping resistance chiefly by *surface deformation*. Their applications are determined by the force vectors of the teeth.

Forceps with **teeth at a 90 degree angle ("surgical forceps")** are, owing to the direction of the main vector, suited for grasping material that can be brought directly *between* the blades (Fig. 2.37). Since no vectors are directed outward, the outer surface of the forceps can be ground smooth so that it forms a blunt instrument when closed (Fig. 2.38a).[22] The *size and sharpness of the teeth* must conform to the thickness and quality of the tissue. Once the teeth have seized the tissue, the working motion is completed, and further action is limited to maintaining this position while the instrument is guided. Thus, complete closure of the jaws is not a criterion for grasping and can be prevented by *stops* as a precaution against tissue injury (Fig. 2.38b, c).

Forceps with **angled teeth ("mouse-tooth forceps")** have a forward-directed vector component (Fig. 2.39a), so the teeth can seize tissue lying *in front of the ends* of the blades. However, the forward vector component requires that a force of equal direction be applied during closure of the forceps, so the working motion is always coupled with a "*thrusting*" *forward motion*. This thrusting motion may encounter a high resistance if the teeth of the mouth-tooth forceps are not perfectly sharp. If the teeth are dull or bent, the forceps can at best be

[22] Function is tested by running the fingertip along the undersurface of the closed blades.

back to index



used as a surgical forceps (Fig. 2.39c). That is why mouse-tooth forceps require as much care in their manufacture and maintenance as cutting instruments.[23]

The function of the mouse-tooth forceps is analogous to that of a *claw*, *anchor*, or *trident* (Fig. 2.40), its various applications depending on the blade position when the instrument is applied:

As a *claw*, the forceps is able to grasp wound edges at an angle, with the advantage that the teeth bite more easily into the tissue than with ordinary surgical forceps. When used on smooth surfaces, it produces a fold.[24]

In its function as an *anchor*, the forceps grips a minimal amount of tissue and thus can grasp surfaces with a minimum of deformation.[25]

As a *trident* it can, without penetrating the tissue, produce a friction that can withstand weaker forces.[26]

The properties of toothed forceps can be combined with those of blunt grasping plates to create a *multipurpose forceps* in one instrument (Fig. 2.41).

Fig. 2.39. **Angled teeth ("mouse teeth")**

a One component of the thrust vector is directed forward (*dark red*).

b Owing to the forward-directed vector, the teeth can penetrate material in front of the tips, such as a flat surface (*left*) or wound margin (*right*).

c Sharp teeth are easily bent by careless handling. This eliminates the forward-directed vector component at the tooth tip, and the teeth cannot bite into flat surfaces. The instrument then behaves as a forceps with straight teeth

[23] Function is tested by inspecting the tooth shape and watching for reflections at the tooth tip (a sign of dulling, see also footnote [29], p. 65).

[24] A typical example of the "claw" function is the grasping of a muscular insertion through the conjunctiva (see Fig. 3.25). Grasping the sclera creates a tissue fold that reduces the volume of the eye and raises the intraocular pressure.

[25] Unlike the claw, the anchor can grasp the sclera without raising a fold.

[26] This resistance is weak but may suffice for placing sutures with an extremely sharp needle. The trident configuration is advantageous in that the teeth need not penetrate the wound edges.

back to index

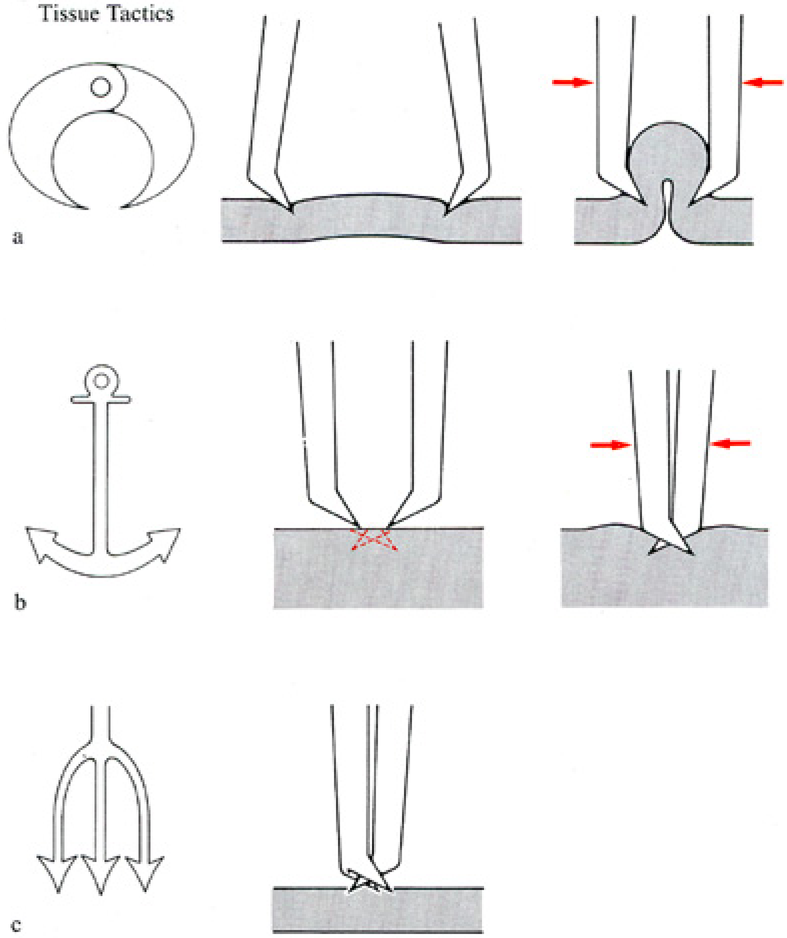


Fig. 2.40. **Possible applications of mouse-tooth forceps**

a Large blade opening: *Claw*. Closure of the blades produces a fold.

b Small blade opening (about one tooth width): *Anchor*. Note that the forceps must be perpendicular to the tissue surface for all the teeth to penetrate evenly.

c Blades closed: *Trident*. When closed, the teeth protrude to form the points of the "trident"

Tying Forceps

Tying forceps should have *rounded side edges* to avoid damage to delicate suture materials. The *tip*, however, should have *sharp edges* so that threads can be picked up from tissue surfaces (Fig. 2.42).

The forceps must be held properly to avoid suture damage. The *tip* area is used only for picking up the thread. If fine suture material cannot be grasped securely, the **blade closure** of the forceps should be checked. Complete closure may be prevented by a slightly *damaged tip* (Fig. 2.43a), by *incarcerated* foreign material (suture remnants, tissue debris, etc.) (Fig. 2.43b), or by overcompression of the handle (Fig. 2.43c).

For further handling the threads are passed over the rounded *side edges*, although these also can act as "cutting edges" if sudden or excessive traction is placed on the threads. When a thread is pulled tightly, therefore, it should not be stretched over sites having a small radius of curvature (Fig. 2.44).

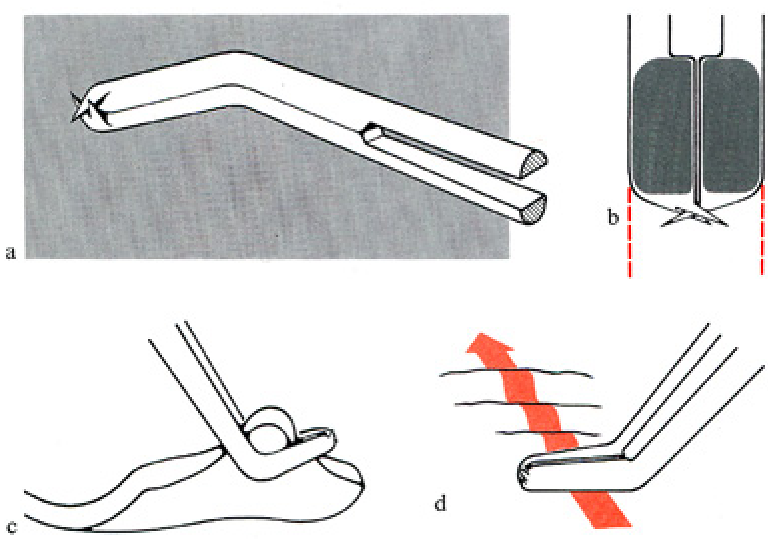


Fig. 2.41. **Applications of a multi-purpose forceps**

a Forceps with mouse teeth, grasping plates, and a handle angulated at the plates. The teeth can perform the claw, anchor, and trident functions described above.

b The grasping plates at the end of the forceps can be used for suture tying, provided they extend far enough laterally beyond the teeth to prevent fouling.

c The angulated grasping plates create "half-ring" blades that can apply traction to the edges of delicate tissue.

d When closed, the instrument can be used as a spatula

back to index

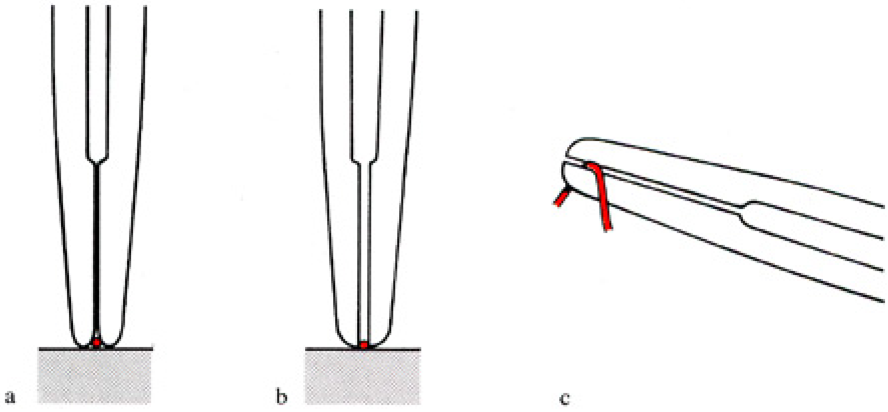


Fig. 2.42. **Tying forceps**

a Rounded tips cannot pick up a thin thread from a flat surface.

b The thread can be grasped only if the jaws meet as far as the tip (sharp edges).

c For handling, the thread is passed over the rounded side edges

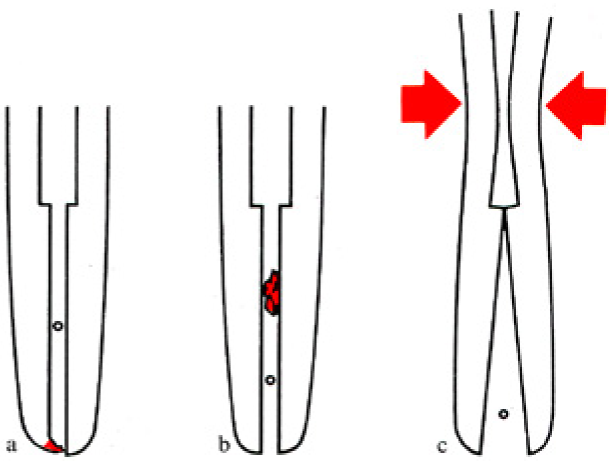


Fig. 2.43. **Reasons for inability to grip fine suture material**

a Damage to the sharp (vulnerable!) tip: A bent edge prevents the jaws from meeting.

b Closure is prevented by foreign material trapped between the blades.

c The jaws gape because of excessive pressure on the handle (see Fig. 2.31 b)

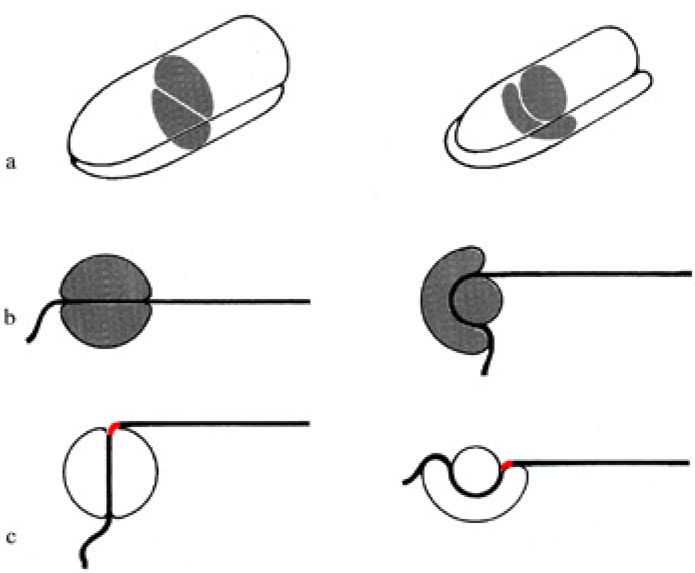


Fig. 2.44. **Technique for holding tying forceps under a high suture tension.** *Left*: Plane forceps. *Right*: Hollowed-blade forceps.

a Jaw configurations (cross-section: *Gray*).

b Risk of suture breakage is minimized by gripping the thread so that it passes over the largest radius of curvature.

c Risk of breakage is high when the thread is passed over sites where the radius of curvature is small (*red*)

Needleholders

If a needle is to pass through tissue, its *resistance* in the holder must be greater than in the tissue. Thus, a holder for use with heavy gauge needles that encounter high tissue resistance must be able to exert a *strong grip*, while a holder for fine, ultrasharp needles must be able to grip the wire *without damage*. When the needle is grasped, the only practical way to produce a sufficiently high frictional resistance is by applying a high pressure. However, there is a significant danger of needle slippage or deformation when a *high-pressure grip* is used.

The danger of **needle deformation** (bending or breaking) is lowest when the cross-sectional shape of the jaws conforms to the curvature of the needle (Fig. 2.45a). However, this means that each needle type would require its own needleholder for very high precision work. For practical reasons this solution is limited to cases in which very fine needles must overcome a relatively high resistance. Ordinarily, compromise designs are sought which permit a single needleholder to be used for multiple needle types (Figs. 2.45d, e and 2.46).

Slippage of the needle is likely to occur if the pressure is not applied at right angles to the needle shaft. This occurs in a diverging jaw opening (Fig. 2.47). It also occurs when the needle is gripped at an oblique angle to the jaw axis and therefore the shape of the jaws will determine the angles at which the needle can be held securely (Fig. 2.48).

The *appropriate construction* of a needleholder depends on the pressure that is to be exerted on the needle. The criteria are more stringent in cases where a high tissue resistance will be encountered than when an ultrasharp needle is passed through soft tissue.[27]

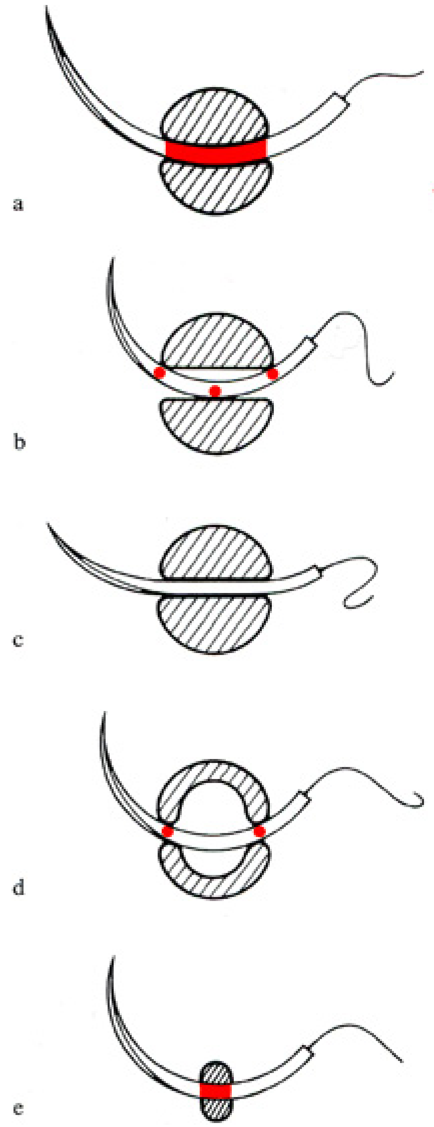


Fig. 2.45. **Cross-section of needleholder jaws**

a The curve of the jaws is congruent to the needle curve. The needle retains its shape even when gripped very tightly.

b Jaws with flat inner surfaces contact a curved needle at only three points.

c Closing the flat jaws will cause the needle to bend or break.

d Hollowed jaws make contact at only two points, so there is less danger of needle damage.

e With very fine, flat jaws, the lack of congruence between needle and jaws is negligible, and there is no danger of needle damage. Very fine jaws provide very little friction and therefore work only with ultrasharp needles that encounter minimal resistance in tissue

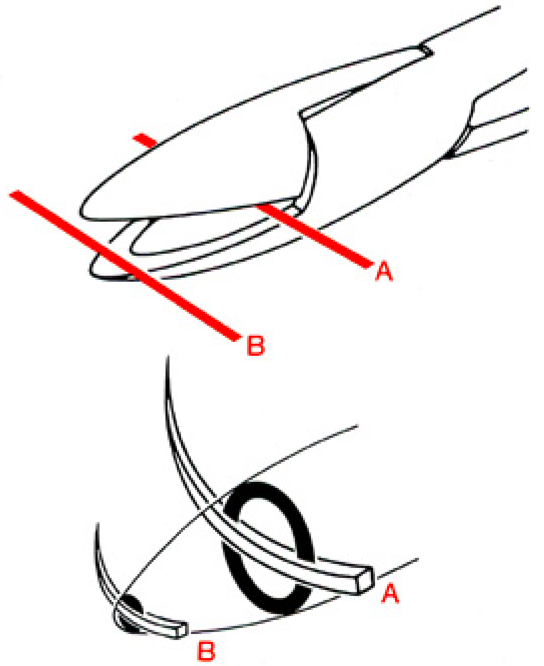


Fig. 2.46. **Multipurpose needleholder for grasping fine and heavier gauge needles.** The jaws have a conical outer shape (narrow at the tip and wider behind) with a deep inner groove.
Heavier gauge needles (*A*) are gripped in the rear part of the jaws close to the hinge (analogous to Fig. 2.45d).
Thin needles (*B*) are grasped with the tip of the jaws (analogous to Fig. 2.45e)

[27] Needleholders for suturing the cornea must meet high precision requirements, while suturing of the conjunctiva may be done with a simple forceps.

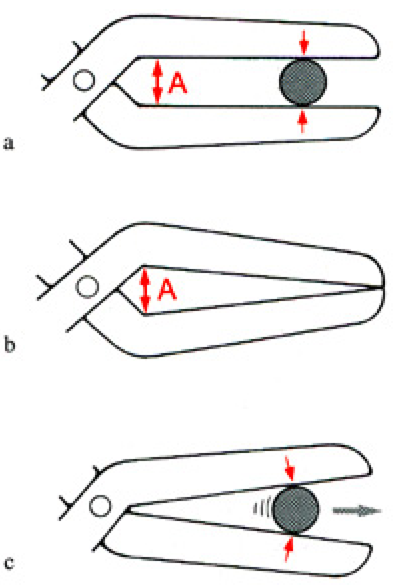


Fig. 2.47. **Direction of gripping vectors in a needleholder**

a When the jaws are parallel on gripping the needle, the forces are applied at right angles, and there are no force vectors that might shift the needle. Therefore the needle is held securely.

b Closure of the empty jaws in such a needleholder leaves a gap near the joint whose size (*A*) determines the needle gauge that can be held securely.

c If there is no gap, the jaws will diverge when gripping a needle, producing oblique force vectors that cause needle expulsion

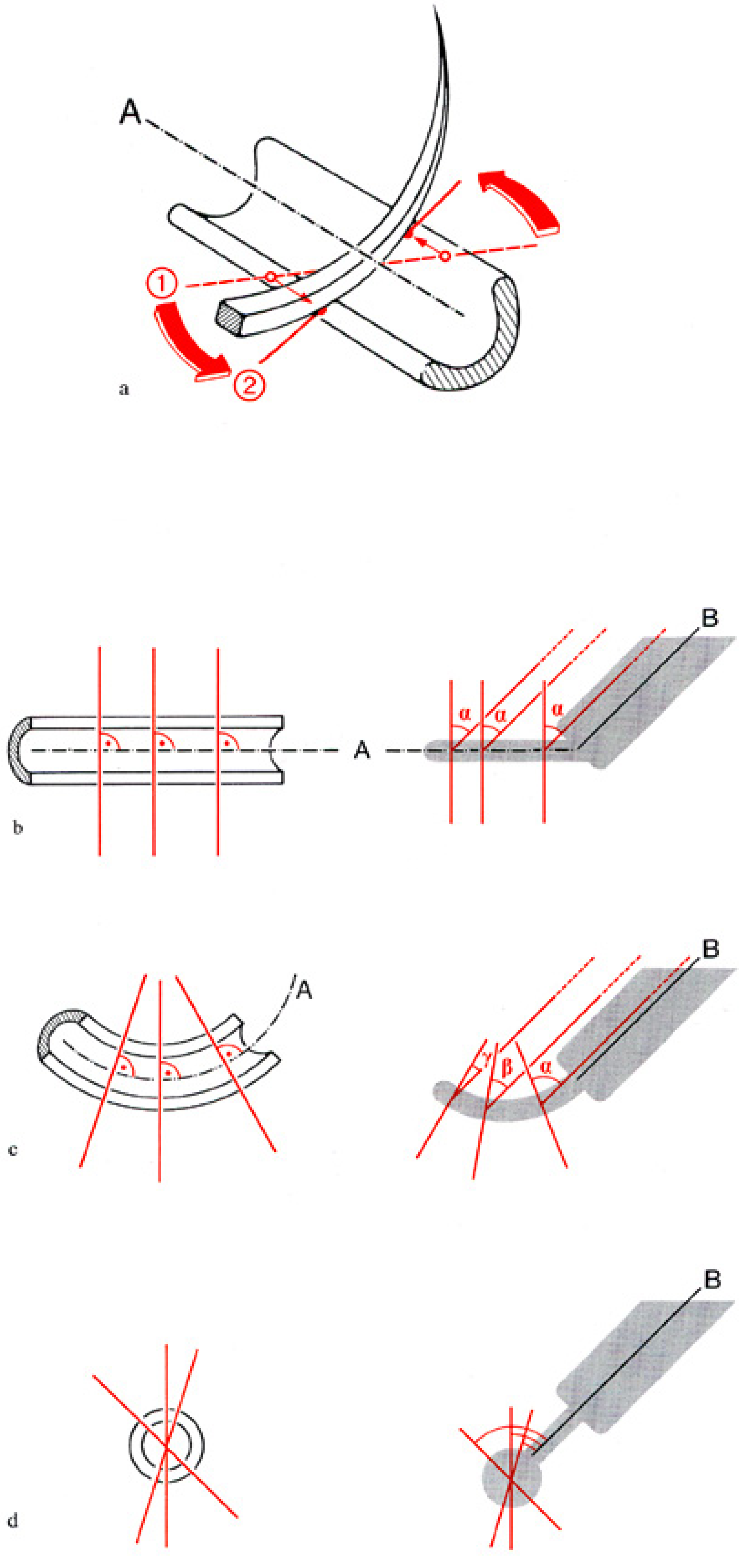


Fig. 2.48. **Angles between needle and axis of needleholder handle** ►

a When gripped obliquely (*1*), curved needles tend to shift until the distance between contact points is minimal, i.e., until they are perpendicular to the jaw axis *A* (*2*).

b In straight jaws there is just one angle at which the needle can be gripped. That is the angle (α) between the jaw axis (*A*) and handle axis (*B*).

c In curved jaws the needle can be gripped at various angles (α, *β*, *γ*) to the handle axis. However, the needle must be held at different places in the jaws for each of the various angles to that it will stay perpendicular to the curved jaw axis (*A*).

d In hemispheric jaws (spoon forceps with a "point" axis, see also Fig. 2.36), the distances between contact points are equal in all directions, so the needle can be gripped at any desired angle to the handle axis

back to index

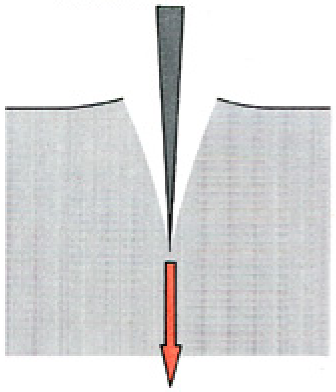


Fig. 2.49. **Cutting**. Tissue fibers are divided by a highly concentrated pressure (pressure of the cutting edge and counter-pressure of the tissue). The properties of the cutting edge determine the quality of the result. The movement of the cutting edge controls the direction in which the tissue is divided

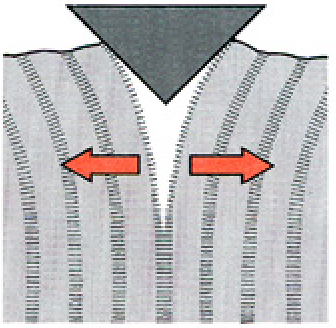


Fig. 2.50. **Splitting (blunt dissection)**. Splitting is rupturing, accomplished by driving a wedge into a preexisting tissue space. The effect depends on the width of the wedge (which determines the force of the dissection) and the properties of the tissue (which define the path of least resistance). The leading edge of the wedge does not touch the fibers to be divided

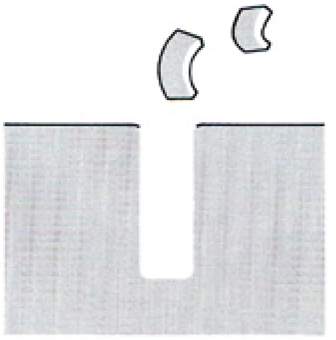


Fig. 2.51. **Division of tissue by removal of material**. The tissue is divided by excavating a "channel" through it

2.1.3 The Division of Tissues

General Techniques

Tissues can be divided by *cutting*, *splitting*, or by the *removal of material*. In **cutting**, the tissue fibers are divided by a direct and concentrated application of pressure. This procedure divides only fibers coming in contact with the cutting edge ("sharp dissection") (Fig. 2.49), so the surgeon can precisely control the cutting process by guidance of the cutting edge.[28]

In division by **splitting** ("blunt dissection"), the tissue fibers are overstretched to the point of rupture. This technique is effective only in *preformed tissue spaces* that provide anatomic paths of low resistance. The split is accomplished by means of a wedge (Fig. 2.50), which forces the more resistant layers apart while causing the loose intervening fibers to rupture without touching them directly. Thus, the properties of the cutting edge are important only in locating a suitable level at which to initiate the split and do not affect the splitting process itself. The latter, incidentally, is not controlled by the shape or movement of the wedge but depends chiefly on the anatomy of the interspaces between firmer tissues. Splitting is appropriate, then, when the surgeon wishes to be guided by the properties of the tissue itself, without "imposing his will upon it."

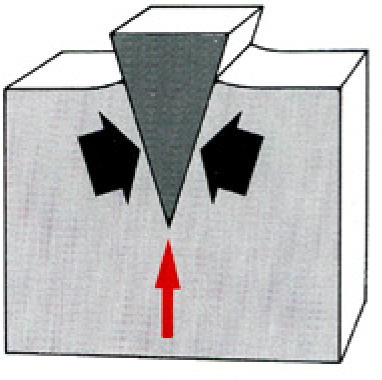
The **removal of material** lying between the parts to be divided (Fig. 2.51) is the basic principle of division by *sawing*, *drilling*, and *burning*. When the divided parts are reunited, the tissue cannot be fully restored to its anatomic state because of the lost material. Therefore, such techniques generally are used in ophthalmic surgery only if the goal of the operation is *dehiscence*.

[28] Whereas splitting can be controlled by tactile feedback, cutting with a very sharp edge relies on perfect visual monitoring because of the low tissue resistance.

Fig. 2.52. **The "cutting ability" of an instrument**

a A cutting instrument consists of a cutting edge and its carrier. The resistance to the cutting edge (*red arrow*) determines the actual cutting ability of the instrument, while the resistance to the carrier (lateral resistance, *black arrows*) determines the ability of the instrument to penetrate into tissue.

b The narrower the wedge, the lower the lateral resistance, but the lower the blade stability as well. The concave blade (*right*) combines high sharpness (low lateral resistance) with high stability (broad back)



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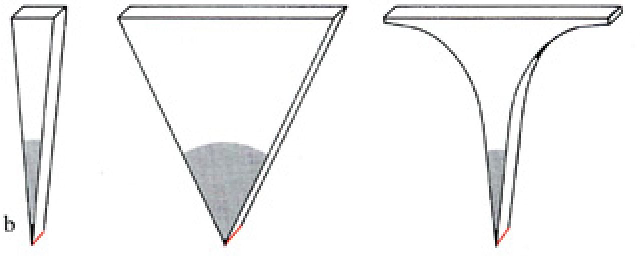

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back to index

Special Problems in Cutting

While in theory the line of an incision should follow the exact path on which the surgeon guides the cutting edge, in reality significant deviations occur. However, by knowing the factors that alter the path taken by a cutting instrument through tissue, the surgeon can incorporate the factors into his operating plan and still achieve the desired precision. These factors are: the shape of the **instrument**, the properties of the **tissue**, and the guidance of the instrument by the **surgeon**. All these factors play a role in determining the facility with which the tissue is divided ("*sharpness*") and the path that the cutting edge follows in the tissue (*the shape of the cut*).

Sharpness is a product of the *cutting ability* of the instrument and the *sectility* of the tissue.

The **cutting ability of instruments** (Fig. 2.52) is determined largely by the cutting edge. If the edge is a geometric point or line (with "zero surface area"), the pressure becomes infinitely high when any force is applied, and the resistance at the edge, (i.e., the *cutting resistance* proper) becomes infinitely low.[29] Additionally, cutting ability is influenced by the carrier, or the part of the instrument that holds the cutting edge. The resistance encountered by the carrier, called the *lateral resistance*, depends on the angle formed by the carrier surfaces (Fig. 2.52b).

The **sectility of tissue** depends on the tendency of the fibers to be severed rather than displaced by an advancing blade (Fig. 2.53a). If the sectility is low, even a sharp blade will seem dull. If a blade is passed through tissue layers of *varying sectility*, only the layers with high sectility are cut while those of low sectility may remain intact (Fig. 2.53b).

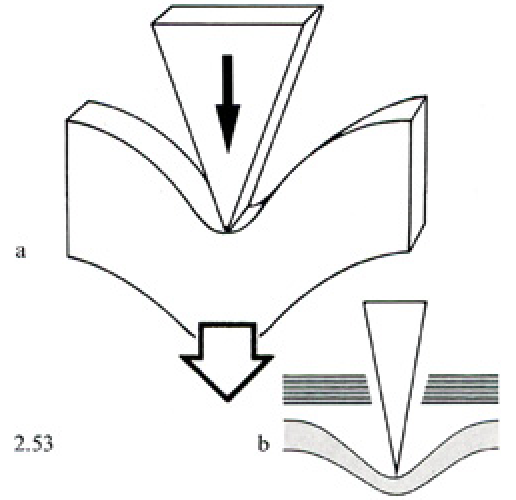


Fig. 2.53. **The "sectility" of tissues**

a Tissue that is very mobile tends to shift ahead of the blade and is not sectioned.

b Practical importance of sectility: If a cutting edge is advanced through successive tissue layers of different sectility, it may divide the layer with high sectility while pushing aside the layer with low sectility

Sectility can be enhanced by any means that keep the tissue from shifting ahead of the cutting edge (Fig. 2.54):

Counterpressure may be provided by mechanical supports – the principle employed in scissors and punches. Increased *tissue tension* also prevents tissue fibers from shifting. Hard eyes, therefore, are more sectile than soft ones. Coun-

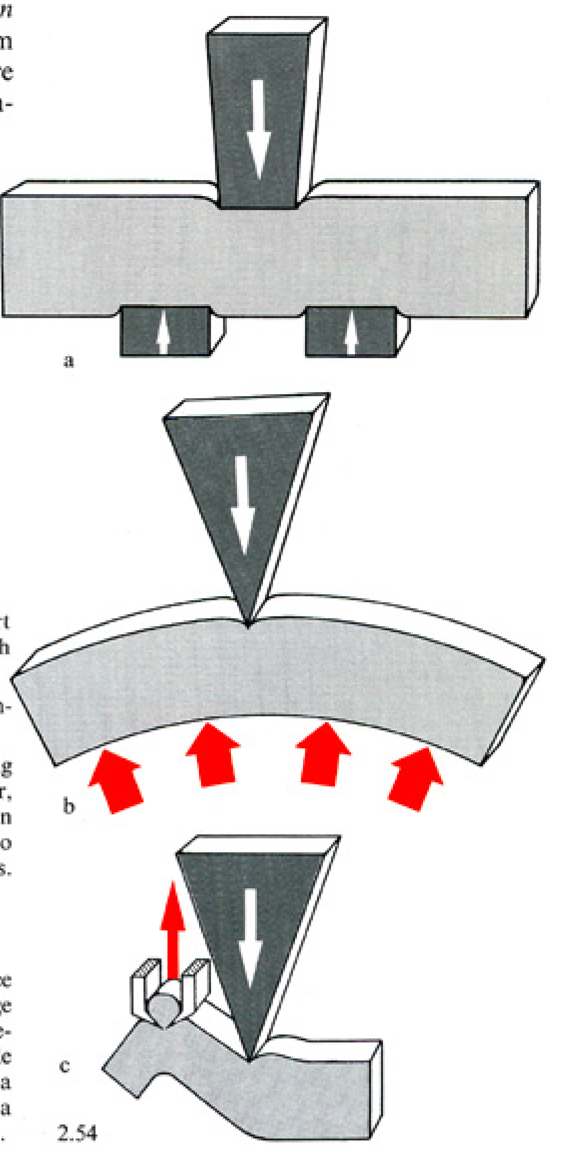


Fig. 2.54. **Methods of improving sectility**

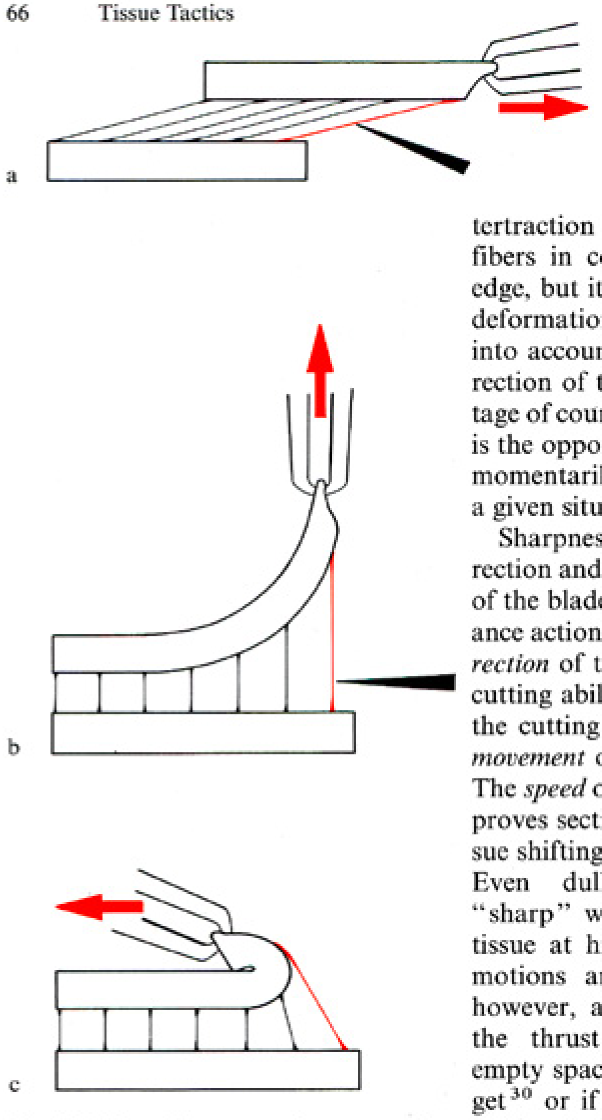
a The jaws of the instrument can support the material from below (here: The punch principle).

b Tissue tension is increased by a high intraocular pressure.

c Tissue tension can be varied by applying countertraction with a forceps. However, this method may cause tissue deformation requiring corrective blade movements to obtain the intended cut (see also Figs. 5.78, 5.81c)

[29] Function test: The absence of surface area on a properly ground cutting edge is evidenced visually by the absence of reflections from it, regardless of the angle of light incidence. A light reflex on a ground edge signifies that the edge has a definite surface area and therefore is dull.

back to index



tertraction with *forceps* keeps the fibers in contact with the cutting edge, but it invariably causes tissue deformation, which must be taken into account when deciding the direction of the cut. A major advantage of countertraction with forceps is the opportunity to adapt sectility momentarily to the requirements of a given situation (Fig. 2.55).

Sharpness also depends on the direction and speed of the movements of the blade and hence on the guidance actions of the surgeon. The *direction* of the movements increases cutting ability when it is parallel to the cutting edge (a "*pull-through*" *movement* of the blade) (Fig. 2.56). The *speed* of the cutting motion improves sectility because it limits tissue shifting through inertial effects. Even dull blades may seem "sharp" when thrust through the tissue at high speed. Rapid blade motions are difficult to control, however, and are safe only when the thrust vectors terminate in empty space after reaching the target[30] or if their magnitude is limited by the instrument design.[31]

The **shape of the finished cut** is determined by the path taken by the cutting edge through the tissue. It might be assumed that the cutting path would match the path on which the surgeon guides the cutting edge (the *guidance path*). But in reality the two paths coincide only under certain conditions, i.e., when the advancing blade cannot push the tissue aside. Otherwise the cut will deviate, and the result will not conform precisely to the surgeon's intent (Fig. 2.57).

Deviations of the cutting path from the guidance path are the result of *asymmetric resistances* in the tissue. As the cutting edge advances, this asymmetry forces the tissue in the direction of the higher resistance. In other words, tissue from the side with the lower resistance "piles up" ahead of the blade, and the cut deviates in the direction of the lower resistance.

If a very precise cut is required, these tendencies must be taken into account when formulating the operating plan. Specifically, the causes of asymmetric resistances must be analyzed as they relate to the design of the instrument, the guidance of

Fig. 2.55. **Use of forceps traction to control sectility in the sharp dissection of tissue layers**

a Diffuse tension: Forceps traction parallel to the tissue surface tenses all fibers along the plane of the dissection; The resistance to the forceps traction is correspondingly high. The sectility of all fibers is increased equally.

b Progressive tension: Perpendicular traction elevates the overlying layer, and the fibers that present to the cutting edge are tensed in progressive fashion. Only the sectility in that zone is increased.

c Selective tension: Reflecting the layer to be dissected restricts tension selectively to the target fibers. The other fibers are less sectile and are protected from inadvertent damage. Because the necessary tension is transmitted to only a few fibers, resistance to the forceps traction is low

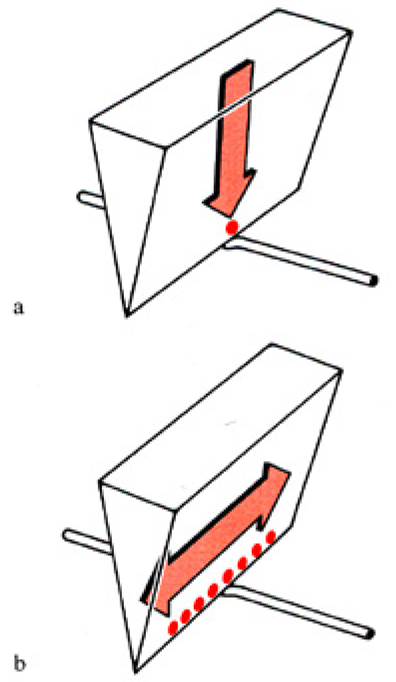


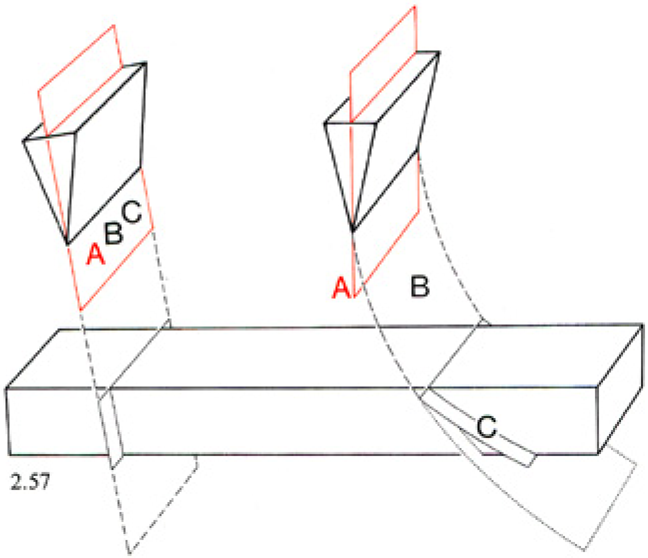
Fig. 2.56. **Concept of the "pull-through" cutting action**

a With a simple thrusting action of the blade, each tissue fiber encounters a single point on the cutting edge (the cutting point, *red*). This action drives the cutting edge into deeper layers, and the cut progresses in depth.

b If the blade is moved parallel to the cutting edge, each fiber is successively exposed to the action of multiple cutting points. This improves cutting ability without deepening the cut

[30] Examples: Needles, cataract knives.
[31] Examples: Vibrating knives, ultrasonic vibrating probes.

back to index



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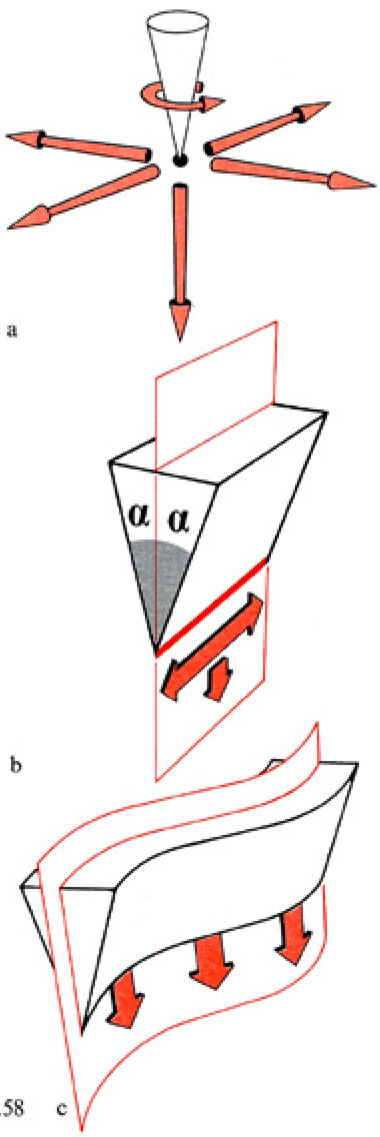

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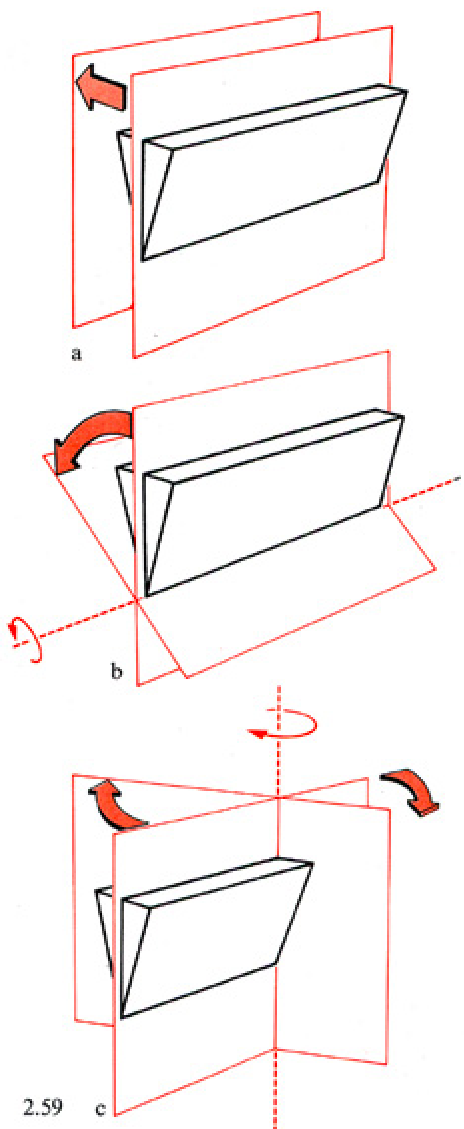

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2.59 c

Fig. 2.57. **Analysis of the cutting process in terms of preferential path, guidance path, and path in the tissue**. The three factors – instrument, surgeon, and tissue – are characterized by three geometric surfaces:

Preferential path (*A*): The path the instrument tends to follow by virtue of its construction.
Guidance path (*B*): The actual path of the cutting edge as directed by the surgeon, characterizing his intent.
Path in the tissue (*C*): The result of the cutting process: the cut surface.

Ideally (*left*) all three surfaces coincide, and the cut surface matches the surgeon's intent. In reality (*right*), the surfaces usually do not coincide because

- the guidance path does not equal the preferential path if the surgeon does not guide the cutting edge precisely along the bisector of the carrier surfaces;
- the path in the tissue does not equal the guidance path if the tissue shifts ahead of the cutting edge

Fig. 2.58. **Motions with symmetrical lateral resistance**

a A single, imaginary cutting point has unlimited mobility. That of a real cutting point is limited by the lateral resistance of its carrier.

b A linear cutting edge describes an imaginary surface as it moves. If the lateral resistance is symmetrical, its motion follows the bisector of the carrier surfaces (the "preferential path"). If this path is a plane (knife) or the surface of a body of revolution (trephine), there are two motions with a symmetrical lateral resistance (*arrows*):

- motion perpendicular to the cutting edge (thrusting; see Fig. 2.56a);
- motion parallel to the cutting edge (pull-through; see Fig. 2.56b).

c If the preferential path is a surface of irregular curvature, the only motion with a symmetrical lateral resistance is thrusting, since any pull-through motion will create vectors perpendicular to the preferential path. Blades of this shape are useful only in punch-like mechanisms

Fig. 2.59. **Motions with asymmetrical lateral resistance**. Any motion of the blade that does not follow the preferential path creates vector components perpendicular to the preferential path, resulting in asymmetrical lateral resistances. This can result from lateral shifting of the blade (**a**), rotation about the axis of the cutting edge (**b**, see also Fig. 2.74), or rotation about an axis perpendicular to the cutting edge (**c**, see also Fig. 2.75)

the instrument, and the properties of the tissue.

The path on which the **blade** encounters symmetric lateral resistances in the tissue is called the *preferential path* of the cutting edge. It lies on a plane that bisects the lateral surfaces of the carrier. This imaginary plane does not represent an actual carrier surface[32] but simply characterizes the path a blade tends to follow by virtue of its design. The motion vectors on the preferential path can be resolved into components perpendicular to the cutting edge (*thrust vectors*) and components parallel to the cutting edge (*pull-through vectors*) (Fig. 2.58). If a blade is not guided precisely along its preferential path, the *lateral resistance* will become *asymmetrical*, increasing on one side of the blade and dwindling on the opposite side (Fig. 2.59).

This has two consequences: First, the cutting instrument is forced back toward the preferential path by the tissue. If the surgeon wishes to keep the blade on the path initiated, he must apply greater force. Second, the tissue fibers ahead of the blade are pushed toward the side of greater resistance, causing the finished cut to deviate toward the side of lesser resistance (Fig. 2.60).[33]

It follows, then, that the *precision* of a cut is greatest when the guidance path (of the surgeon) is congruent with the preferential path (of the instrument).[34] In practical terms this means that when the sur-

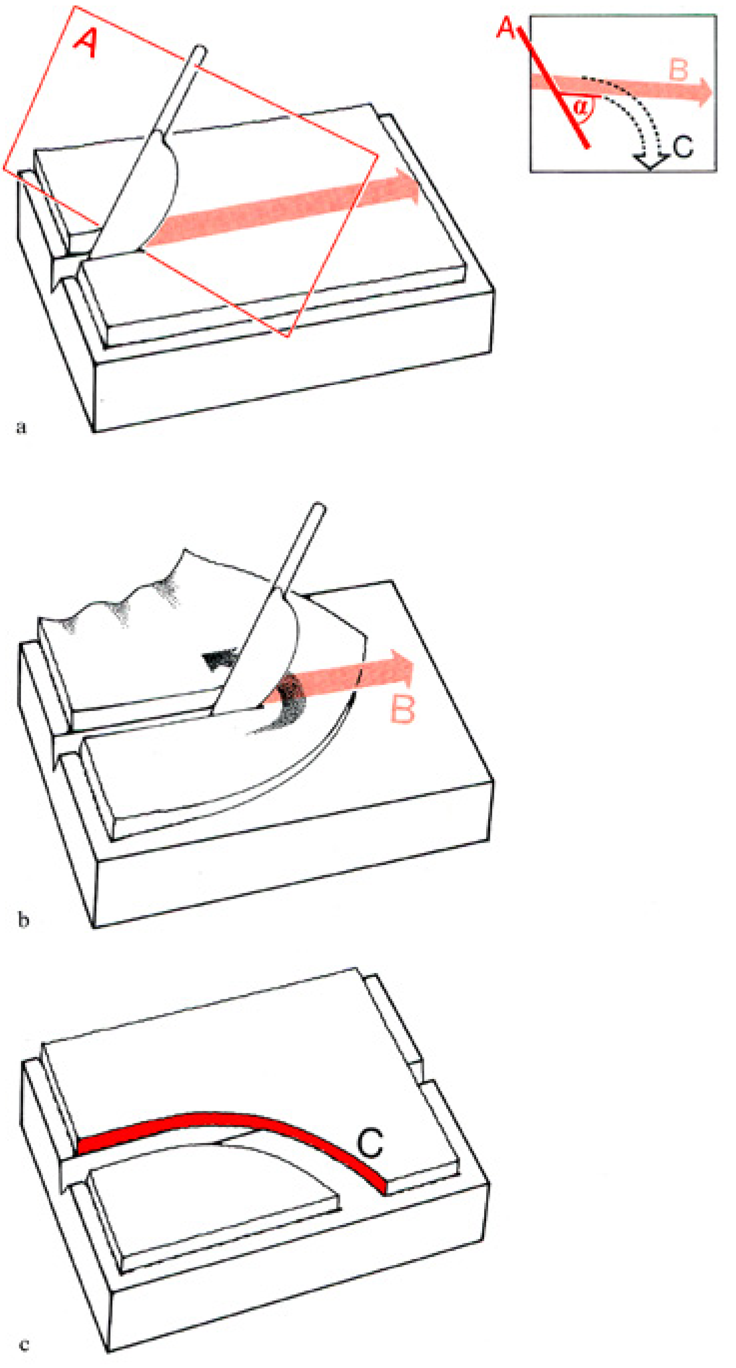

Fig. 2.60. **Deviation of the cut due to asymmetrical lateral resistance.** If the blade is maneuvered so that the guidance path (*B*) forms an angle with the preferential path (*A*), the path in the tissue (*C*) deviates from the intended direction (*inset*) and tends increasingly to follow the preferential path (where the lateral resistance is again symmetrical).

a Blade guided at an angle to the preferential path (outlined in *red*).

b The tissue ahead of the cutting edge shifts toward the side with the higher resistance.

c The finished cut deviates toward the side of the lower resistance

[32] If the cutting edge is a point, the preferential path of the instrument is a geometric line.

[33] When the surgeon becomes aware by tactile feedback that greater force is needed to keep the blade on the initiated path, he may assume that deviation is occurring.

[34] Examples: A plane guidance path for cataract knives and keratomes, a cylindrical guidance path for trephines.

back to index

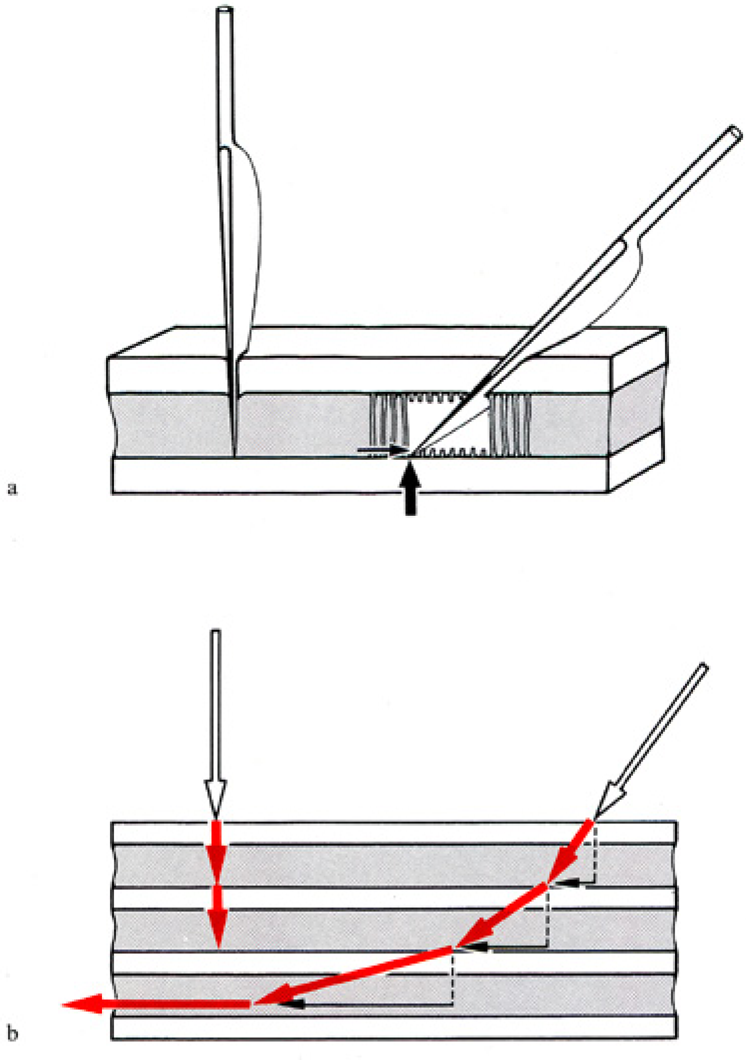

Fig. 2.61. **Lamellar deflection. a** Position of blade, **b** path in the lamellae. Lamellar tissues consist of a regular arrangement of layers with varying resistances. A blade directed through the layers at a right angle (*left*) encounters a symmetrical lateral resistance and can advance in the intended direction. If the cut is started obliquely (*right*), the lateral resistance is asymmetrical because it is higher at the lamellae than in the interlamellar space. The path in the tissue deviates more and more until it terminates parallel to the lamellae in an interlamellar layer, where lateral resistance is again symmetrical

geon wishes to direct the blade *along the preferential path* (of the instrument), it is helpful to maximize the lateral resistance (either by selection of the blade shape or the manner of holding the blade), for this makes it easier to continue the cut in a given direction and reduces the danger of inadvertent deviations (Fig. 2.74).

If the cutting edge is *not guided along its preferential path*, as when curved incisions must be made for which there is no congruent blade, it is necessary to cope with the problems of an asymmetric lateral resistance. These problems can be reduced by making the lateral resistance as low as possible. This is done by selecting a blade with a small carrier surface and guiding it so that only a small part of the blade enters the tissue (see Fig. 2.74).

The second major source of asymmetric lateral resistances is in the **tissue**, the causes being either the structure of the tissue itself (*nonhomogeneities*) or external *stresses* imposed on the tissue by the surgeon. Both cause incisions to deviate in typical, predictable ways.

In **lamellar tissues**, for example, the resistance to a cutting edge is lower in the direction of the lamination than at right angles to it. As a result, the incision is progressively deflected onto a path parallel to the tissue layers (Fig. 2.61). The surgeon can influence the tendency toward *lamellar deflection* by regulating the effective "sharpness" of the cut. *Blunt* cutting conditions (i.e., low cutting ability of the blade combined with low sectility of the tissue) promote lamellar deflection and are advantageous when the surgical goal is the dissection of tissue *layers.*[35] *Sharp* cutting conditions are advantageous when it is necessary to cut *across the lamellae.*[36]

Other typical sectile characteristics are found in **compliant, resilient tissues**. When these tissues are under uniform tension, they tend to be pushed forward by the blade (Fig. 2.62) so that the resulting incision is shorter than the distance traveled by the cutting edge.[37] Consequently, the cutting movement must be carried past the target to obtain an incision of the desired length.

When compliant, resilient tissue is under *asymmetric tension*, it tends

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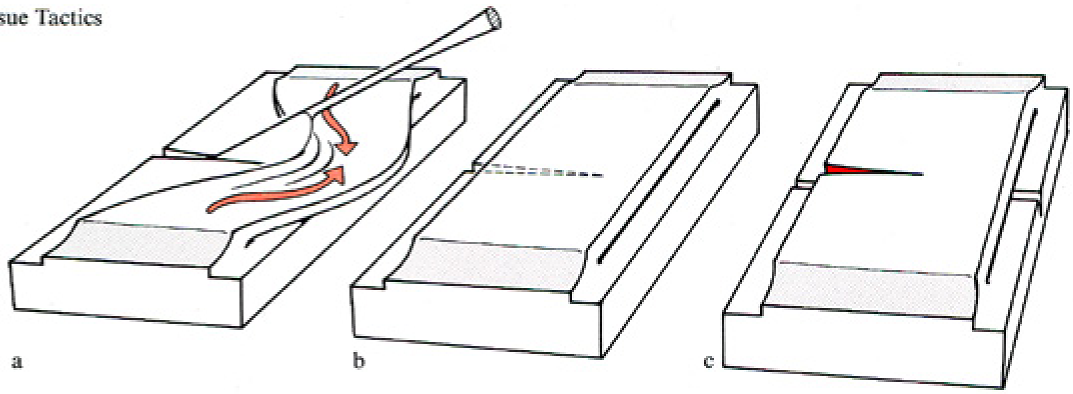
[35] Example: Lowering the intraocular pressure by medication or by puncture of the anterior chamber in lamellar corneal grafting.

[36] Example: If the anterior chamber must be opened when the intraocular pressure is low, lamellar deflection can prevent the blade from reaching the anterior chamber at all. Therefore the intraocular pressure must be raised.

[37] This explains why penetrating foreign bodies "cut" openings that are smaller than their own diameter. Extraction of the foreign body usually necessitates extension of the entry wound.



a b c

Fig. 2.62. **Forward shifting tendency**. In the model, a mobile tissue layer loosely overlies a substrate of firm tissue. The layers are adherent to each other in the gray zones.

a The loose tissue layer is shifted ahead of the blade.

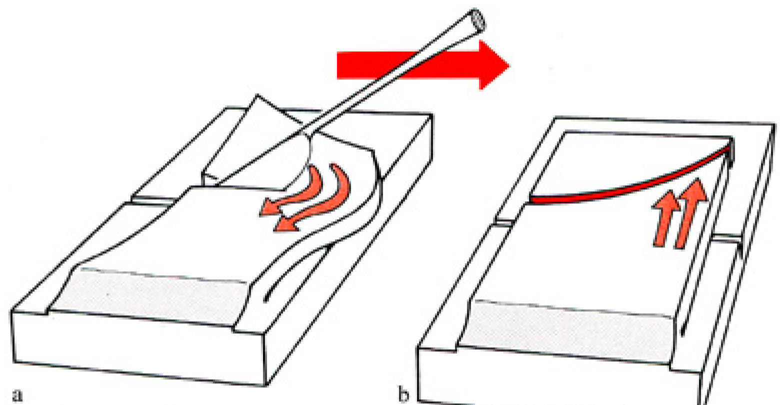
b With a short cutting stroke, the length of the incision in the firm sublayer equals the distance traveled by the cutting edge, but the mobile layer remains intact (see also Fig. 2.53).

c A longer cutting stroke incises the mobile layer as well, but the incision is shorter than the distance traveled by the blade.

Note: When symmetrical tissue tension is present, the cut follows the direction of the guidance path

to shift also laterally, causing the cut to deviate toward the side of lesser tension (Fig. 2.63). This asymmetry of tensions is encountered whenever loose tissue is fixed on one side, whether anatomically,[38] by scar tissue, or by the surgeon himself with fixation instruments.

These shifting tendencies can be reduced by making the tissue tense before cutting, thereby increasing its sectility. However, this introduces yet another mechanism which may cause the cut to deviate from the guidance path: **tissue retraction**. Compliant, resilient tissue will temporarily elongate when tension is applied to it. Releasing the tension restores the tissue to its former shape, and all distances are again shortened in proportion to the initial degree of stretch (Fig. 2.64). *Incisions* made in the stretched tissue are shifted from their original position toward the zone of fixation,[39] and excisional defects are diminished in area. This *retractile tendency* may become a source of un-

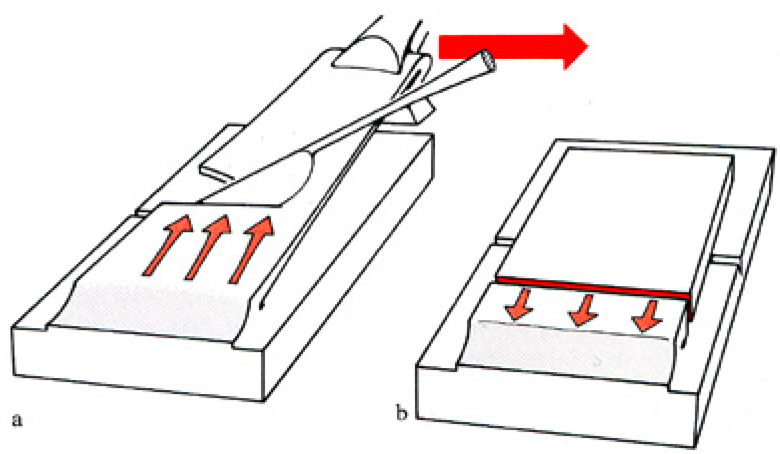


a b

Fig. 2.63. **Lateral shifting tendency**

a If tensions on the tissue are asymmetrical, the mobile tissue will shift ahead of the cutting edge toward the side of higher tension, i.e., toward the zone of fixation (*gray*).

b The resulting incision in the mobile layer deviates toward the opposite side, away from the zone of fixation. In contrast the incision in the firm layer coincides with the guidance path



a b

Fig. 2.64. **Tendency of retraction**. If the tissue is divided while stretched (**a**), the resulting incision will shift toward the zone of fixation after the tension is released (**b**)

[38] Example: Fixation of the conjunctiva at the limbus, fixation of the iris at the iris root.

[39] Example: Shifting of incisions toward the limbus or iris root.

❮ ❯

anticipated changes in the shape and location of incisions, but it can also be exploited to achieve specific goals.[40]

Blades with a Point Cutting Edge

Owing to their great freedom of movement, "point" cutting edges (Fig. 2.65) can produce *incisions of any shape* desired. The preferential path of the instrument and the guidance paths are identical in all directions, and an incision is made wherever the point of the blade is directed (Fig. 2.66). A two-dimensional effect can be achieved by making a series of closely spaced linear cuts (Fig. 2.67).

However, as soon as the blade penetrates more deeply into the tissue, the *shape of the carrier* becomes a factor, and lateral resistance is introduced. If the carrier is *conical*, this resistance is equal in all directions (Fig. 2.58a). If the carrier is *prismatic*, the resistance depends on the position of the largest carrier cross-section relative to the guidance direction (Fig. 2.68). By rotating the blade, then, the surgeon can vary the resistance and modify the "sharpness" of the blade as needed (Figs. 2.69, 2.70).

Blades with a point cutting edge are extremely versatile cutting instruments, but they are also very delicate and subject to rapid wear. That is why the blades are constructed of material that is highly wear-resistant (diamond) or easily replaced (razor blade fragments).[41]

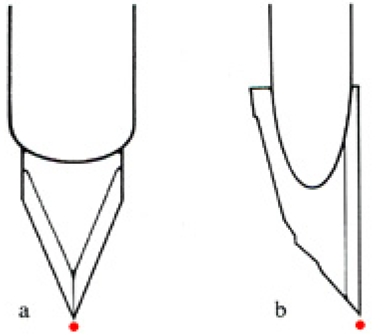


Fig. 2.65. **Blades with a "point cutting edge"** **a** Diamond knife. **b** Razor blade fragment in a holder

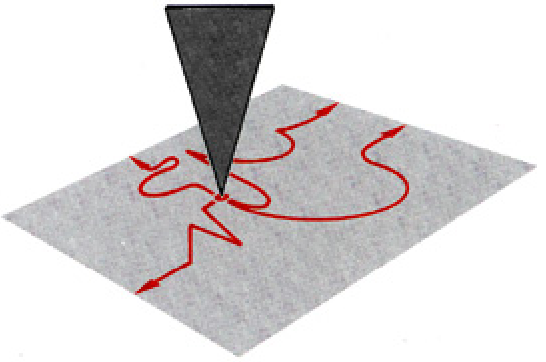


Fig. 2.66. **Cutting characteristics of a point cutting edge.** If only the sharp point of the blade cuts the tissue (i.e., if the blade does not penetrate so deeply that the shape of the carrier becomes a factor), the lateral resistance is symmetrical in all directions, and the number of preferential paths is infinitely large. Cutting conditions are ideal in almost all guidance directions, i.e., the preferential path and guidance path are congruent. The surgeon can use the point cutting edge like a pencil to "draw" an incised line of arbitrary shape

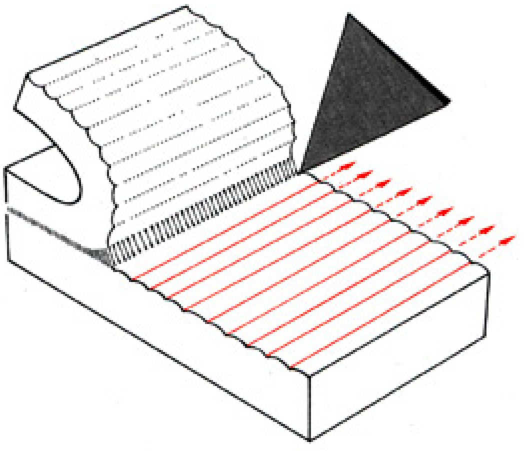


Fig. 2.67. **Technique of using a point cutting edge.** A plane of sharp dissection can be established by making a series of closely spaced linear incisions. The resulting cut surface has a "hatched" appearance

[40] Example: Excising the iris very close to its base when making a peripheral iridectomy (see Fig. 7.21a).
[41] Only if the point cutting edges are used exclusively in the "thrusting" mode, such as the points of keratomes, cataract knifes or needles, the problem of wear is reduced.

back to index

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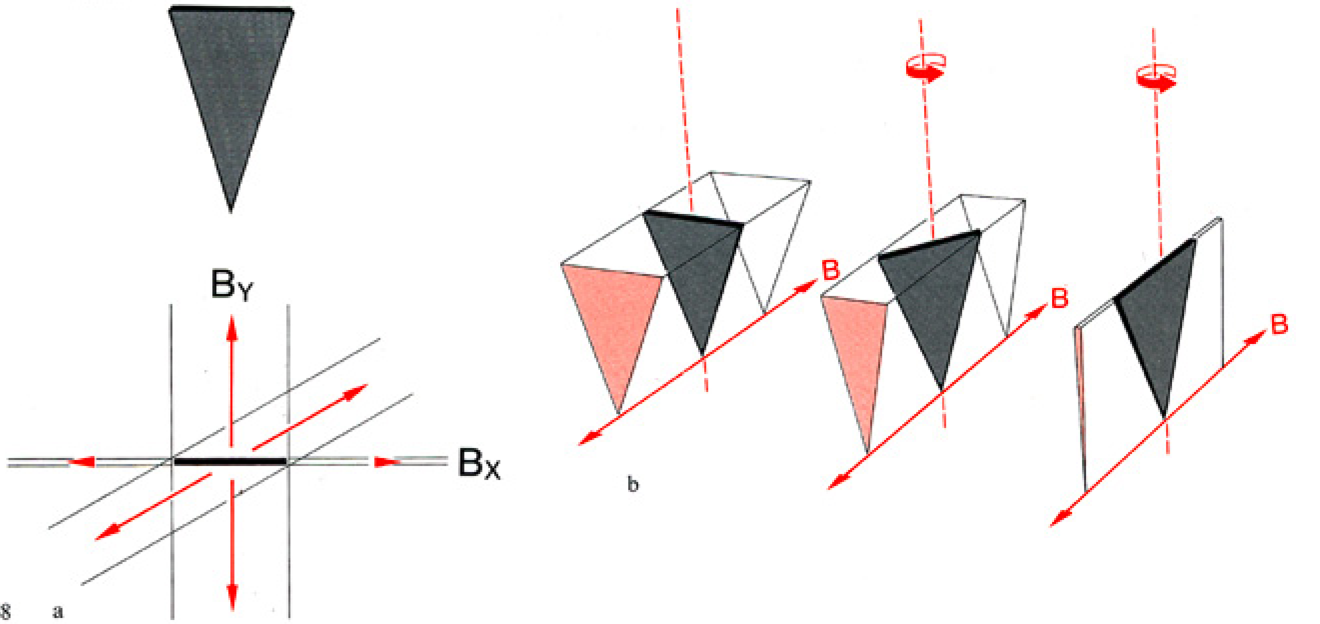
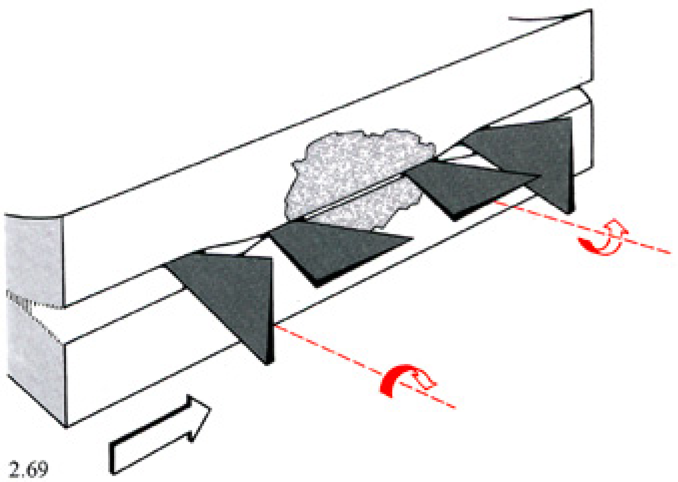


2.68 a b

Fig. 2.68. **Lateral resistance of blades with a point cutting edge**

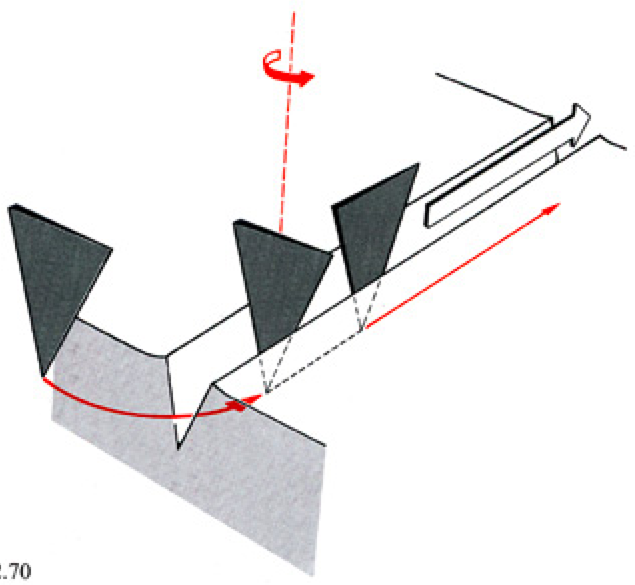
a With a prismatic carrier, the lateral resistance increases with the width of the blade surface projected in the guidance direction. Thus, lateral resistance is maximal when the widest blade surface is perpendicular to the guidance direction (B_Y) and minimal when the widest blade surface is parallel to the guidance direction (B_X).

b Lateral resistance can be changed from maximal (*left*) to minimal (*right*) simply by rotating the blade. *B*: Guidance direction



2.69

Fig. 2.69. **Modifying the lateral resistance, illustrated for the dissection of lamellae fused by scar tissue**. The blade is kept on the interlamellar plane by directing it in "blunt" fashion (see Fig. 2.68 b, *left*). To overcome the higher and irregular resistance of the scar (*gray*), the blade is rotated into a "sharp" position (see Fig. 2.68 b, *right*)



2.70

Fig. 2.70. **Modifying the lateral resistance, illustrated for inserting a blade into a precut groove.** The blade needs to be inserted so that the cutting edge will reach the base of the groove without injuring the walls. This is done by holding the blade with its broadest surface perpendicular to the guidance direction, thereby decreasing its effective sharpness. At the base of the groove, maximal sharpness is needed to deepen the incision, so the blade is rotated until its broadest surface is parallel to the guidance direction (*red arrow*)

back to index

Knives with a Linear Cutting Edge

Knives are characterized by a linear cutting edge. Different blade configurations (Fig. 2.71) differ in the *longitudinal profile* of the cutting edge, which determines the angle at which each cutting point attacks the tissue (Fig. 2.72), and also in the shape of the *carrier surfaces*, which determines the lateral resistance (Fig. 2.73).

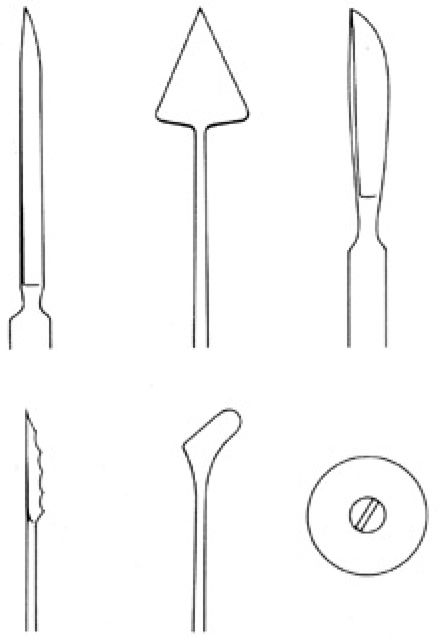


Fig. 2.71. **Knives with linear cutting edges.** *Top row*: Cataract knife, keratoma, scalpel. *Bottom row*: Serrated knife, hockey knife, circular knife

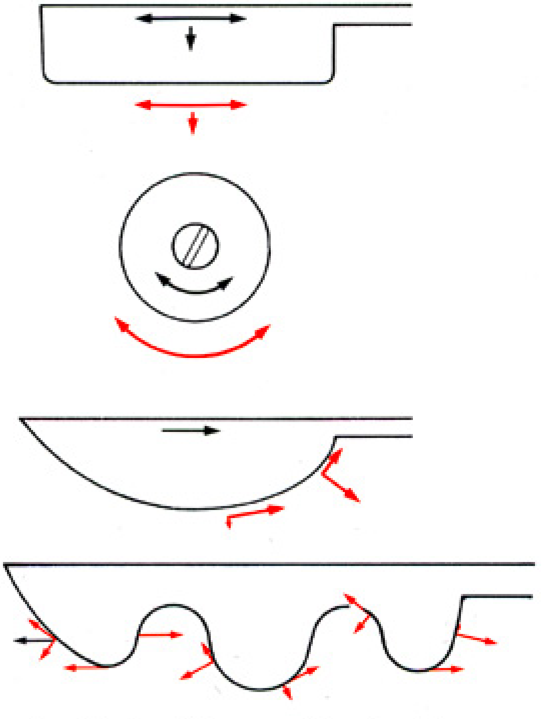


Fig. 2.72. **Attack angles of various blades.** A pure thrusting motion is possible only with a straight, linear cutting edge; a pure pull-through motion can be made with straight as well as circular edges. For all other edge shapes, every blade motion produces a combination of both vectors. In the serrated edge (*bottom*), this principle is exploited most fully to maximize the cutting ability of the blade

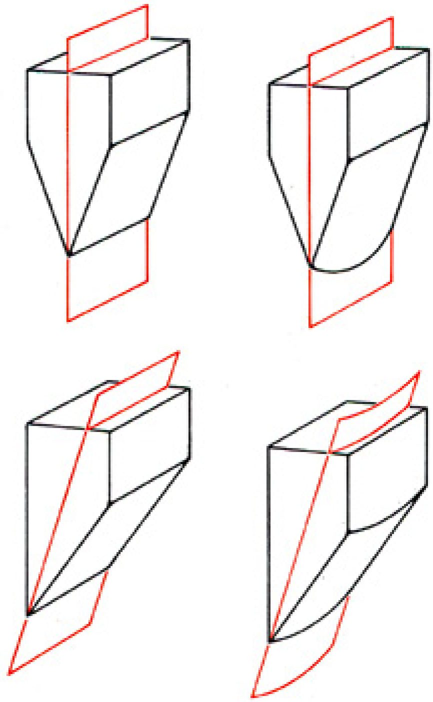


Fig. 2.73. **Preferential paths of linear blades**
Top row: All symmetrically ground blades have a plane preferential path regardless of the shape of the cutting edge.
Bottom row: Asymmetrically ground blades have a plane preferential path only if the cutting edge is straight. This path is off-angle to the main carrier axis, however, and if the edge is directed along this axis, it will encounter an asymmetrical lateral resistance (*left*). Asymmetrical blades with a curved cutting edge differ from simple knifes in that their preferential path is arched (*right*). This is not a problem if the blade is used at tissue surfaces, but if it penetrates more deeply the cutting properties become complex

When the lateral resistances on the blade are symmetrical, the resulting cut surface is a *plane*. A straight incision, then, is obtained by holding the blade such that a maximum amount of blade surface comes between the edges of the incision. For a curved incision, on the other hand, only a small amount of blade surface should penetrate the tissue (Fig. 2.74). When the direction of the incision is changed, the smoothest cut surfaces are obtained by turning the blade so that the cutting edge itself forms the axis of rotation (Fig. 2.75).

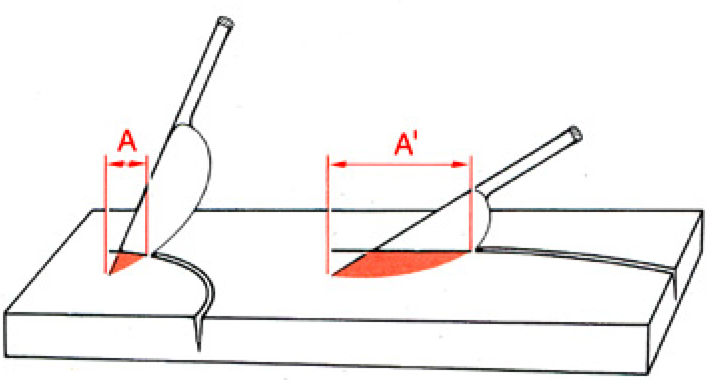


Fig. 2.74. **Blade position for making curved incisions**. To obtain a curved cut surface that differs in shape from the plane preferential path, lateral resistance must be minimized. *Left*: An upright blade position decreases lateral resistance and allows the incision to be curved. *Right*: A low blade position tends to produce a straighter cut. *A*, *A'* length of blade immersed in tissue

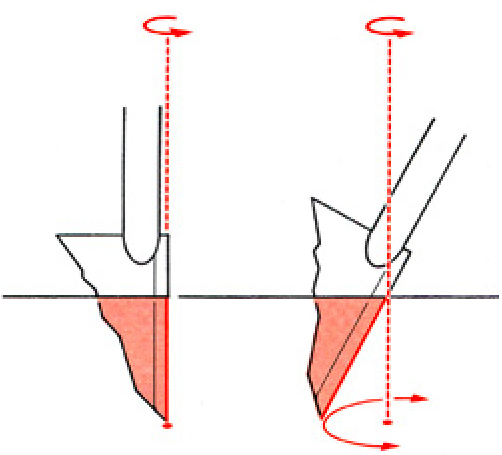


Fig. 2.75. **Axis of rotation for direction changes**. If the cutting edge itself forms the axis of rotation, a smooth cut surface is produced (*left*). But if the cutting edge is off the axis, each cutting point has a different radius of rotation, and an irregular cut surface is obtained (*right*)

back to index

Scissors

The cutting properties of *scissors* are quite complex in that the combination of two blades does not simply represent the sum of their individual cutting properties but forms an entirely new instrument with unique characteristics (Fig. 2.76).

A scissors can divide tissue in three different ways:

- by closing the blades
- by opening the blades
- with the tip of the blades.

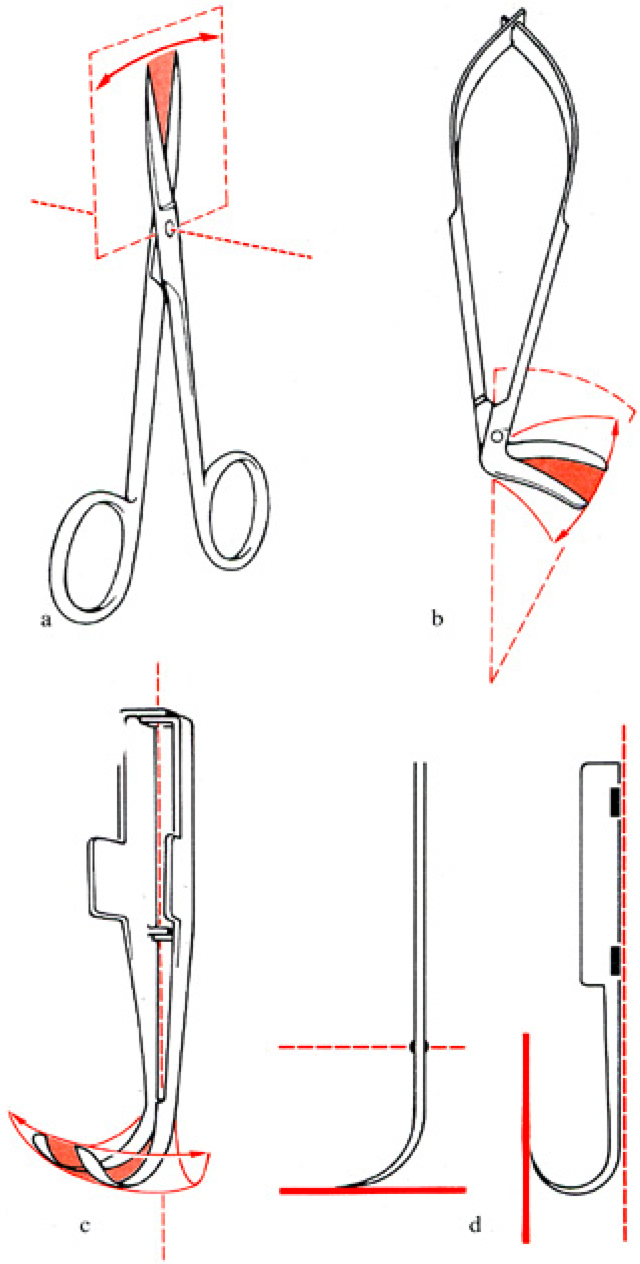


Fig. 2.76. **Types of scissors**. A scissors consists of two opposing blades connected by a screw joint. The handles and blades can be combined in various ways. The position of the joint determines the maximum allowable blade curvature. The guidance path (on which the cutting edges are guided during the working motion) is determined and constrained by the construction of the instrument. *White areas outlined in red*: Guidance path of blades during opening. *Red area between the blades*: Guidance path during closure. *Arrow*: Guidance line of blade tips.

a Straight scissors with ringed handles and simple screw joint. The guidance path is plane.

b Angled, curved scissors with a spring handle. The guidance path is the surface of a cone.

c Hinge-handle scissors with deeply curved blades.

d Relation between blade curvature and joint position. The blade curve is the maximum possible when the tangent to the blade tip (*red line*) is parallel to the joint axis (*broken line*). At greater curvature the blade tips will meet before the scissors is completely closed. With a simple screw joint, the maximum allowable curvature is 90° (*left*); with a hinge handle, 180° (*right*)

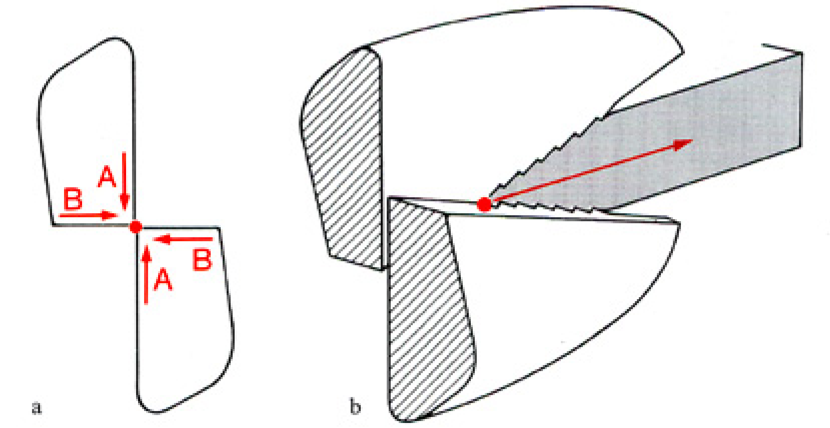


Fig. 2.77. **Principle of cutting by closure of the scissors**

a The ground edges of the blades meet at the cutting point, formed by vector component *A* perpendicular to the joint axis (closing motion of scissors) and vector component *B* parallel to the joint axis (shearing stress).

b The cutting point moves forward, dividing the tissue presented to it by the closing blades. Meanwhile the tissue is held steady by the squeezing action of the blades (symbolized by barbs in the drawing)

Note: The edges of the blades are actually blunt[42]

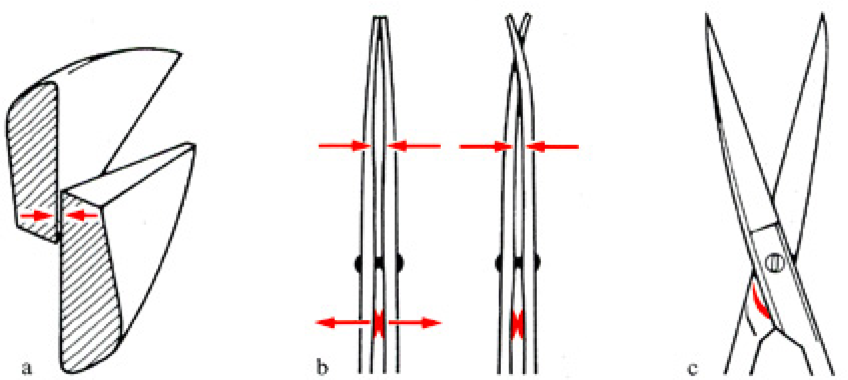


Fig. 2.78. **Analysis of production of shearing stress**

a The stress keeps the edges of the blades pressed together.

b Spring tension is created by the camber of the blades. The side view clearly shows that the blades meet only at a single point. A block (*red*) on the opposite side of the joint helps to maintain the shearing stress. *Left*: Scissors closed; *right*: Scissors half-open.

c Open scissors showing the position of the block (*red*)

Cutting by Closing the Blades

In this, the basic mechanism of scissor cuts, the tissue is divided by a **cutting point** (Fig. 2.77). The *preferential path* then is a line that can assume arbitrary shapes.[43] Scissors are extremely versatile, therefore. However, they cut with a cutting point only in very thin ("two-dimensional") tissue layers such as conjunctiva, lens capsule, iris, and cornea thinned by partial-thickness incision. In thick tissue layers such as full-thickness cornea and sclera, there is a phase, prior to formation of the cutting point during closure, in which the properties of the two individual cutting edges predominate. The preferential paths of the cutting edges are not lines but planes which cut in a direction different from that of the cutting point.

The *cutting point* is formed by the two blade edges pressing against each other during closure (Fig. 2.78). One vector component of the pressing force is created by the shearing stress associated with the scissors construction, the other by the closing action itself. The *shearing stress* is created by the camber of the blades and is reinforced by a block on the opposite side of the joint.[44] This stress largely determines the cutting ability of the scissors, since a cutting point exists only if the force pressing the edges together is greater than the tissue resistance pushing them apart.[45]

The **profile of the scissors cut** results from the *movement of the cutting edges* against the cutting point and the *concomitant tissue movements* induced by the action of the instrument. The blade edges themselves are blunt. They exert a cutting action only if they crush the tissue sufficiently to increase its sec-

[42] The finish of the blade edges serves mainly to ensure a smooth working action. Some roughness is acceptable since the friction will prevent tissue slippage and thereby enhance "sharpness" (principle of serrated hairdressing scissors).

[43] Thus, scissors function neither by the "bite" mechanism where two linear cutting edges simultaneously appose for their full length nor by the "punch" mechanism where a linear cutting edge is pressed against a base.

[44] In scissors that do not have this block, tension must be maintained by manual pressure. Such scissors are usually designed for right-handed use; left-handed operators require special models.

[45] Thus, the cutting ability of the scissors cannot be judged by visual inspection of the blade edges. This can only be tested by function, i.e., making trial cuts in a tissue-like material (such as a soft, moist paper towel).

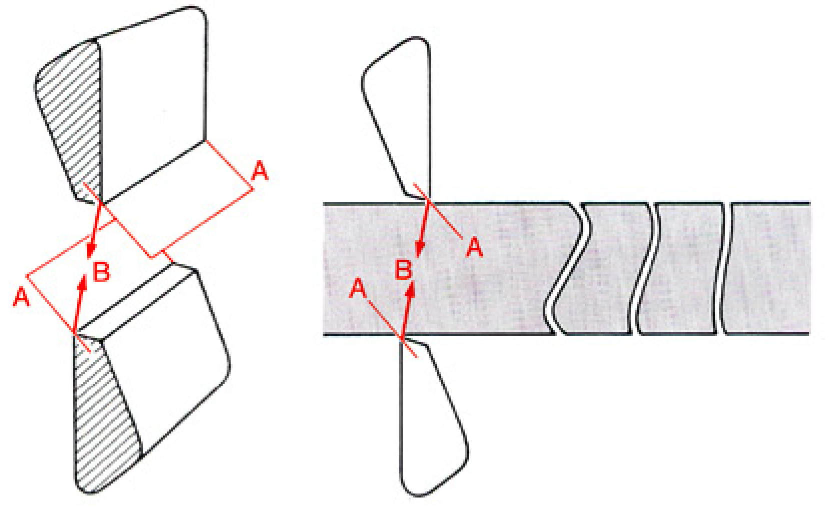
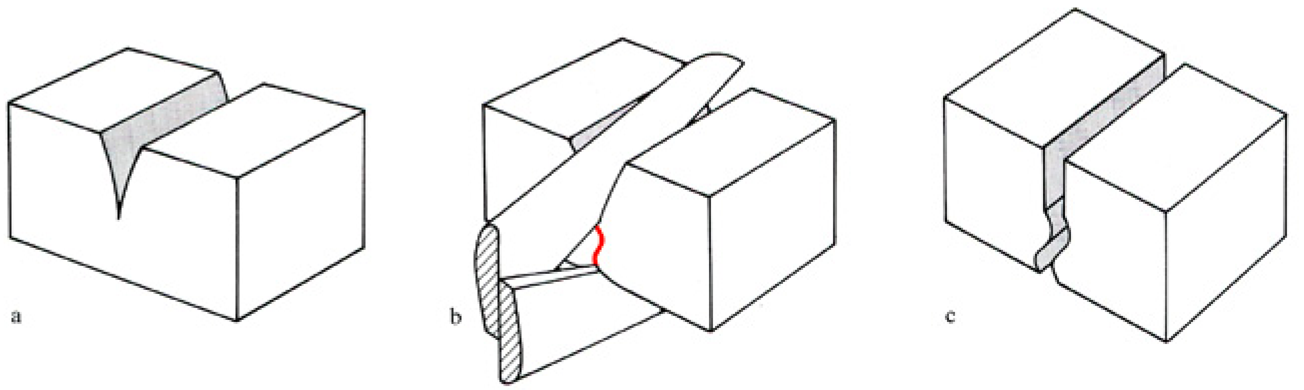


Fig. 2.79. **Profile of a scissors cut**. Both the cutting point and the cutting properties of the blades are important in thick tissue layers. In all scissors, an angle exists between the guidance direction *B* and the preferential path of the edge *A*.[46] This results in an S-shaped cut whose curvature depends on the resistance, mobility, and thickness of the tissue. *Note*: The obliquity of the guidance path *B* results from the camber of the blades



a

b

c

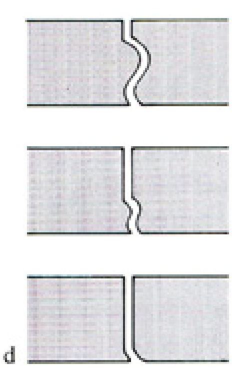
Fig. 2.80. **Preliminary thinning of tissue layers**

a Preliminary cutting with a knife yields a straight cut profile.

b If the preliminary cut is completed with a scissors, the new cut profile is not straight like the knife cut but is curved in accordance with the cutting properties of scissors.

c The result is always a "step" in the incision.

d The size and shape of the step depend on the thickness of the tissue layer left by the preliminary cut. Three examples show the results with superficial (*top*), medium (*center*), and deep (*bottom*) preliminary cuts



d

tility. Because the guidance path of the scissors does not coincide with the preferential path of the edges, the profile of a scissors cut in thick tissue is *S-shaped* (Fig. 2.79). The thicker the tissue layer to be divided, the more pronounced this curvature (Fig. 2.80). The cut profile is also affected by the "sharpness" of the cutting process and by the mobility of the tissue layers. Both factors change as closure proceeds. At the start of the cut, when the blade angle is large, they are not the same as at the conclusion when the blade angle is small. The cut profile changes accordingly.

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[46] Remember: The preferential path of the single blade is the bisector of the ground edges.

back to index

Fig. 2.81. **Analysis of scissors closure**

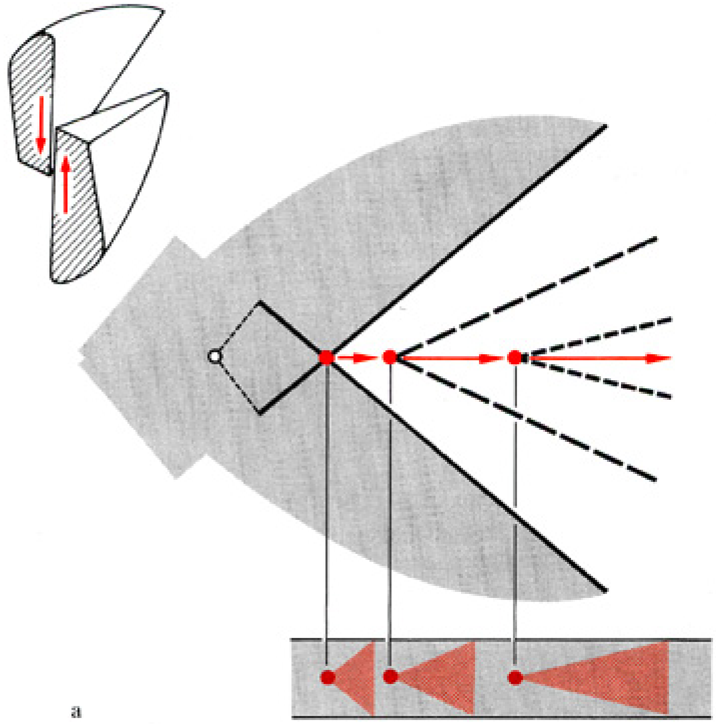
a Closure of the scissors produces the second vector component needed to form the cutting point (*top*). As this point moves forward (*center*), the aperture angle between the blades, and thus the angle of attack at the tissue, is progressively reduced (*bottom*).

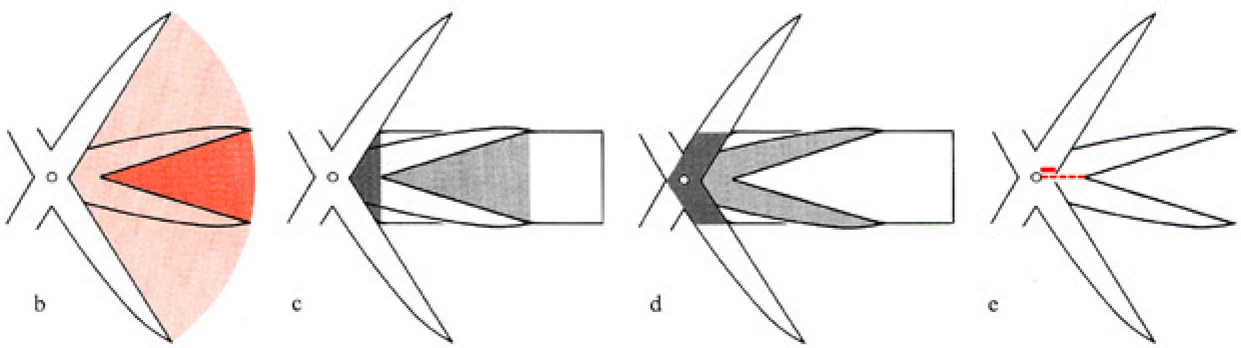
b As closure proceeds the interblade area (*red*) diminishes, and the danger of inadvertent tissue lesions is reduced.

c The amount of tissue lying between the blades (*gray*) increases, and with it the resistance to closure. The tissue tends to shift ahead of the cutting point.

d The immersed blade area (*gray*) increases, and there is a proportional increase in lateral resistance. Lateral deviations of the blades become more difficult.

e The lever arm between the joint and cutting point (*solid red line*) lengthens (*broken red line*), while the lever on the other side of the joint (the handle side) remains constant. As a result, progressively less force is transmitted by the fingers





The **longitudinal scissors cut** is produced by *forward motion of the cutting point*. When the blades are held at a fixed angle, this advancing motion can be produced simply by *pushing* the scissors forward; the shape of the cut then conforms precisely to the *guidance motion* of the operator. This can be successfully done only with a low, uniform tissue resistance.

When tissue resistance is high, the cutting point must be advanced by *closure* of the scissors (the *working motion*) (Fig. 2.81 a). The cutting point moves forward along the blade edges, producing a cut whose shape conforms to the *curvature of the blades*.

During closure of the scissors, the aperture angle of the blades decreases while the amount of tissue between the blades increases. As this occurs, the tissue offers mounting resistance to blade closure, and there is increasing *resistance to the advance of the cutting point* (Fig. 2.81 c).[47] The *lateral resistance* also rises, making it more difficult to change the direction of the cut (Fig. 2.81 d). Meanwhile, the force transmitted to the cutting point diminishes (Fig. 2.81 e). Consequently the sharpness and versatility of the scissors decline steadily as closure proceeds.

If the proposed **shape of the cut** is to *conform* to the shape of the blades, the cut can be performed in one maneuver by a simple closing movement of the scissors. The rising lateral resistance is advantageous for it helps to keep the scissors on the intended path.

[47] This working resistance is directed against the advance of the cutting point and against the squeezing action of the blades, i.e., against movements with forward-directed vector components. It causes the tissue to shift toward the blade tip, and the final cut is shorter than planned. So with a high resistance, the scissors must be forcibly thrust forward to press the tissue against the cutting point and avoid undesired shortening of the cut.

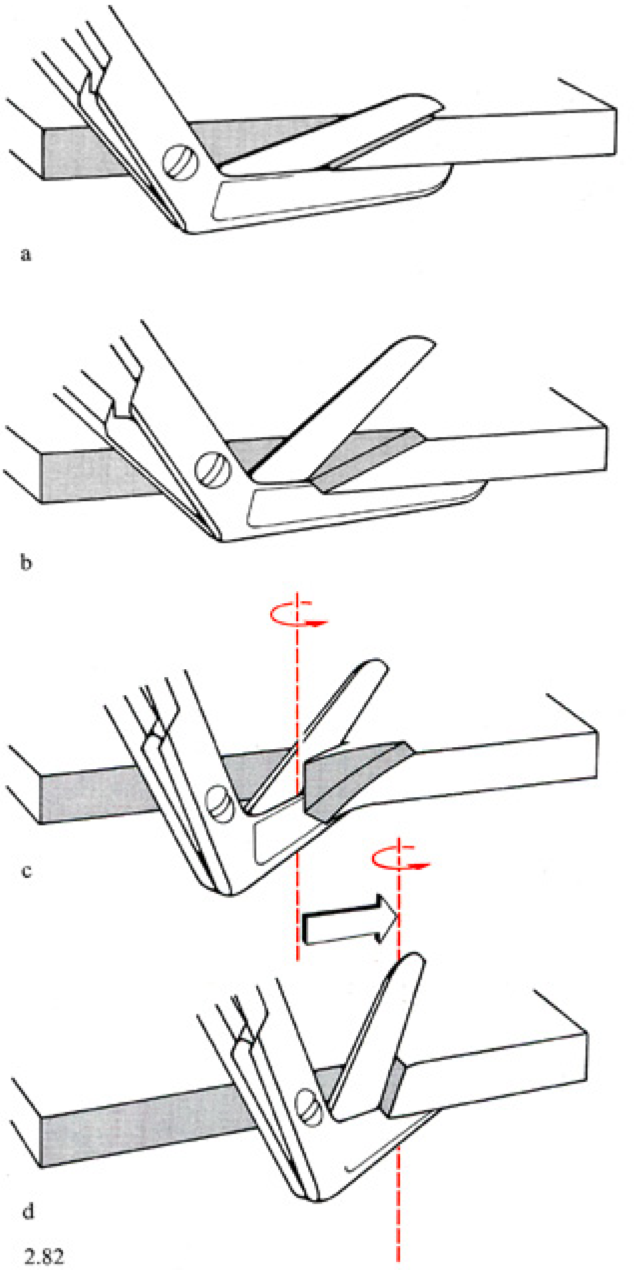
Fig. 2.82. **Reapplying the scissors when cutting in steps**

a Incomplete closure of the blades leaves a partially divided wedge of tissue.

b When the blades are reapplied, their aperture angle is larger than the angle of the tissue wedge.

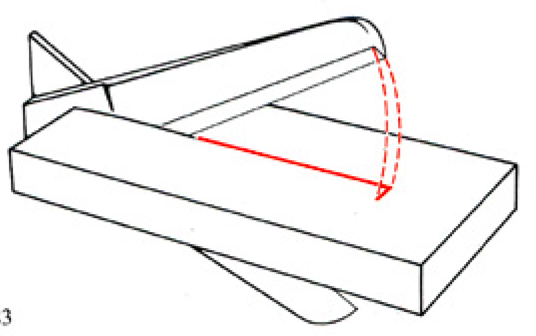
c If the guidance direction is changed when the scissors is reapplied (*narrow arrow*), the partially divided tissue wedge creates a serration.

d This is avoided by first continuing the cut in the original direction (*wide arrow*) after reapplying the scissors, and not turning the scissors in the new direction until the tissue wedge is completely divided



2.82

But if the shape of the cut is to *deviate* from the shape of the blades, it is necessary to combine the closing motion with one or more guidance motions. Here it is advantageous to maintain a large blade aperture, for this reduces lateral resistance and makes it easier to change the direction of the cut. A large aperture angle is maintained by only partially closing the scissors and then reapplying it to the tissue with the blades widely opened. However, with each reapplication of the scissors and thus with each abrupt *change in the aperture angle*, there is an associated change in resistance and tissue mobility. The result is an abrupt change in the profile of the cut. This *serration effect* relates to the working motion of the instrument and is unavoidable when the cut is performed in multiple steps. Another type of serration is based on guidance motions, and this type can be avoided by carefully following the original direction of the cut when the blades are reapplied to the tissue (Fig. 2.82) and by avoiding complete closure of the blades (Fig. 2.83).



2.83

Fig. 2.83. **Serration effect on complete closure of the scissors.** If the scissors tip penetrates completely into the tissue, its leading edge acts as a cutting edge and produces a small lateral cut

back to index

In summary, the *advantages* of the scissors cut are *versatility*, or the ability to make cuts of arbitrary shape, and the effective *sharpness* provided by the crushing action of the blades, which keeps tissues from shifting away from the cutting point. Another advantage is *safety*, since the instrument will divide only tissue lying between the blades. This eliminates the risk of inadvertent lesions outside the interblade area (Fig. 2.81 b); the safety margin can be increased by cutting with a small blade aperture.[48]

The *disadvantages* of the scissors cut correlate with the thickness of the tissue to be divided. Consequently they can be reduced by making a preliminary, partial-thickness incision in thick tissue layers. The thinner the remaining layer, the lower the resistance, and the more regular the profile of the finished cut (Fig. 2.80d). A thinned tissue layer actually maximizes the advantages noted above.

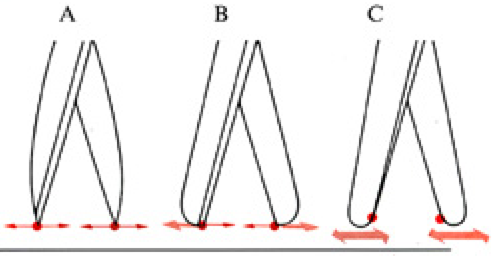
Cutting by Opening the Blades

In this technique the scissors cut with the *back of the blades*. This converts the scissors to a *blunt instrument* suitable for the **splitting** (blunt dissection) of preexisting tissue spaces. Their advantage over simple wedge-shaped instruments is that each blade utilizes the resistance produced in the tissue by the opposing blade, so this technique can open spaces that are crossed by extremely distensible fibers.[49] Although the shape of the resulting "cut" depends chiefly on the path of least tissue resistance, it is prudent to adapt the guidance path of the blades (by the choice of blade shape and position) to the intended shape of the cut to avoid unintentional trauma to surrounding tissues.[50]

Cutting with the Blade Tips

Cutting with the blade tips may just involve the **final phase of cutting by scissors closure**, in which tissue is sectioned by the cutting point. If the outermost ends of the blades are to be used, a scissors is required whose ground edges extend all the way to the tips (i.e., sharp or semirounded scissors, Fig. 2.84A, B). But cutting with the blade tips in a strict sense means using them as **instruments in their own right**. They can be *thrust forward* into tissue as a prelude to cutting by opening or closing the blades: Sharp points can force their way through the tissue in the guidance direction,[51] while blunt tips behave as spatulas and will not damage surrounding structures when the blades are introduced into cavities or spaces.[52] When moved in the *lateral direction* (movement effected by opening or closing the blades), the tips behave as blunt or sharp instruments depending on their shape and position. *Sharp tips* act as point cutting edges regardless of their direction of motion (Fig. 2.84A). They produce linear incisions and differ

Fig. 2.84. **Shapes of scissors tips**



	A	B	C
Shape of blade tips	sharp	semirounded	rounded
Ground edge extends to extremity of blade?	yes	yes	no
Action of blade tips when *thrust* into tissue			
– with blades open (preparatory to cutting by closure of scissors)	sharp	mostly sharp	blunt
– with blades closed (preparatory to cutting by opening the scissors)	sharp	blunt	blunt
Cutting actions of tips during *working motion*:			
– closure of scissors	sharp	sharp	blunt
– opening of scissors	sharp	blunt	blunt

Red dots: Ends of the ground edge; *thin arrows*: "Sharp" movements of the tips; *thick arrows*: Blunt movements.

[48] Example: Trimming suture ends after tying. Cutting with the scissors almost closed (i.e., cutting close to the tip) reduces the risk of damage to tissues or other threads.
[49] Example: Separation of episcleral fibers in operations for strabismus or retinal detachment (see Fig. 4.11); separation of epiretinal membranes in vitrectomies.
[50] Example: In enucleations, lesions of orbital tissue are avoided by using curved blades and holding the scissors snugly against the globe when opening them.
[51] Examples: "Pointed" scissors for penetrating the lens capsule; piercing the iris for iridotomies.
[52] Examples: Muscle scissors for advancing along the globe surface in the episcleral space; corneal scissors for introduction into the anterior chamber (see Fig. 5.53).

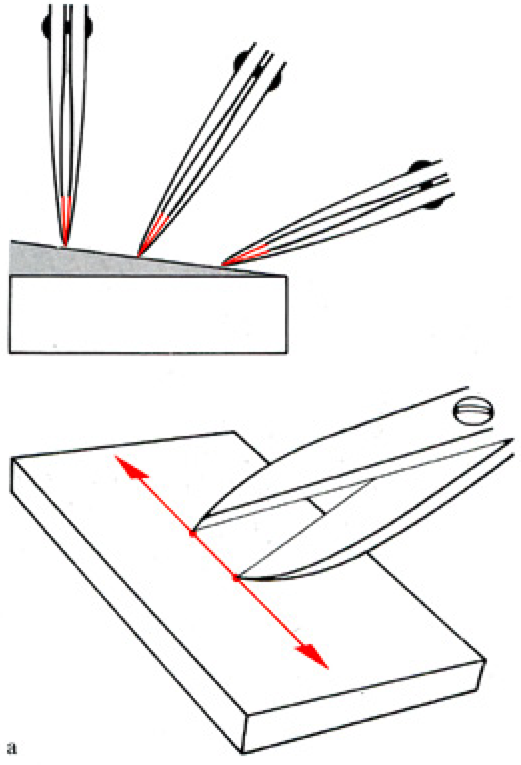
back to index

from free point cutting edges only in that their path is limited by the construction of the scissors. *Rounded tips* are blunt in any direction (Fig. 2.84C). The cutting ability of *semirounded tips* depends on the leading edge: The tip is blunt during opening but sharp during closure (Fig. 2.84B). In addition, the effective sharpness during cutting with the blade tips depends on the *position* in which they are held: While sharp points will cut tissue with the scissors held in any position, thicker-bladed scissors must be applied perpendicular to the tissue surface (Fig. 2.85).

Fig. 2.85. **Cutting with the blade tips**

a When a sharp-pointed scissors is used to cut fibers (*gray*) on hard underlying tissue (*white*) (e.g., episcleral fibers on the sclera), the cutting edge can meet the tissue fibers at any angle and can make a sharp cut in any position (*thin arrow*).

b With nonpointed tips, the cutting point (*red*) stands away from the fibers by the thickness of the blade, and the tips behave as blunt instruments (*thick arrow*). The cutting point can act on the fibers directly only if the blades are applied perpendicular to the tissue surface (see Fig. 4.13)



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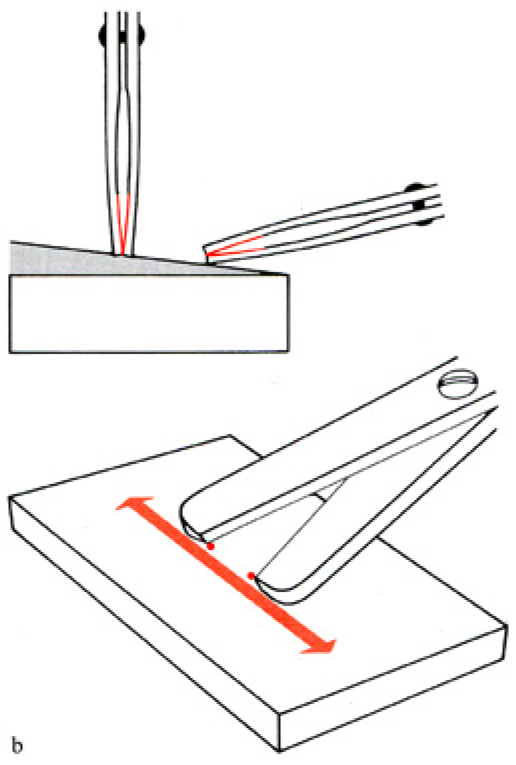

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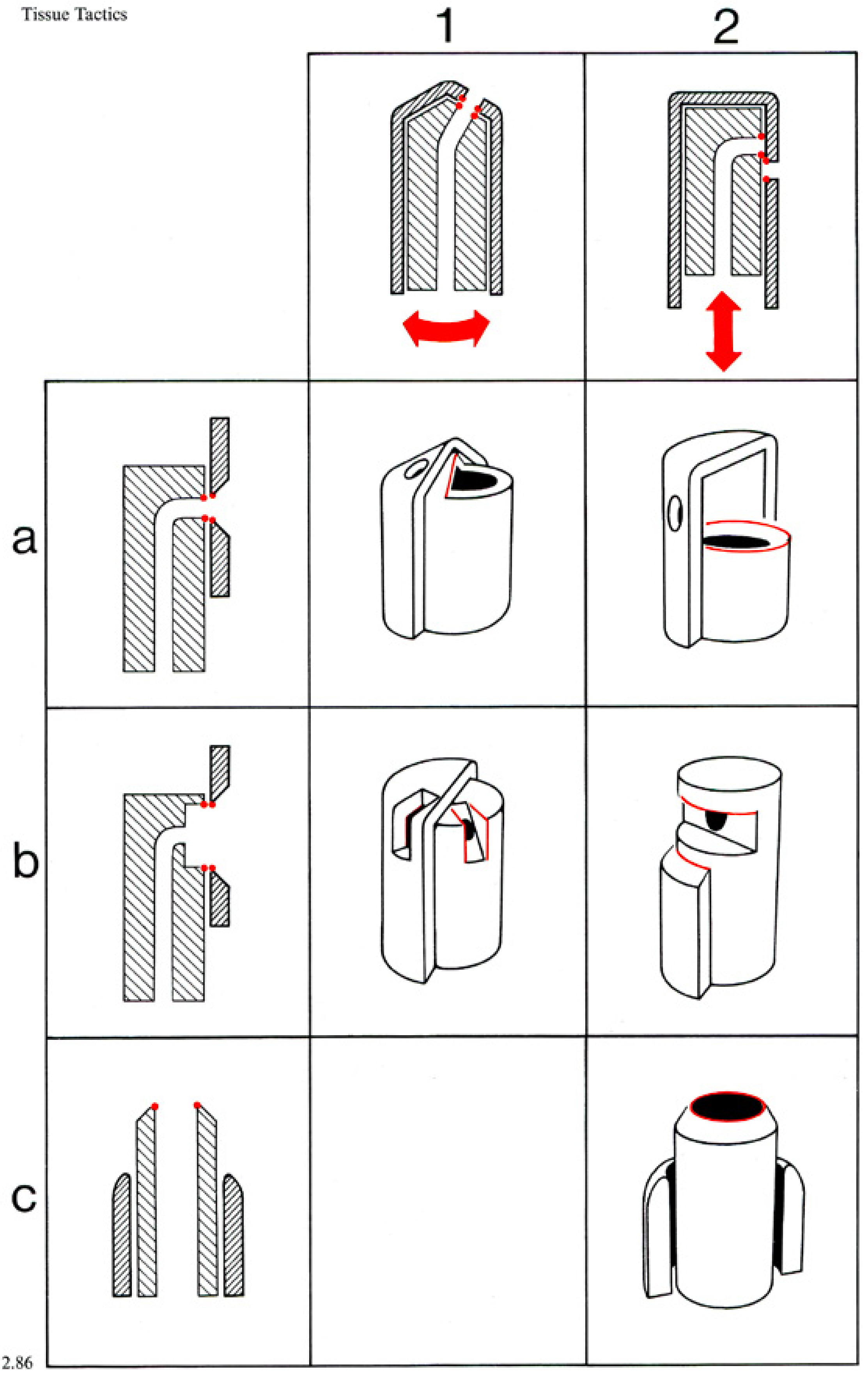
back to index



2.86

Suction Cutters

Suction cutters are miniaturized instruments that combine the functions of grasping, cutting, and transport in a very small volume (Fig. 2.86). The working end of the instrument contains an *aspiration port*, a *resection port*, and a *transport channel*. If space permits, fluid inflow can be provided through a coaxial sleeve (suction infusion cutter).

These miniaturized instruments are not easy to monitor because there is no tactile feedback from the cutting action; visual feedback must be based on the observation of the effects in the tissue[53] and this means that it will be too late to react in case indesired effects occur.

Consequently, one must **anticipate the results** and predict them based on the knowledge of the functional characteristics of the instruments. In order to determine the requirements as to instrument design and handling, one should define whether the goal of a given action is **cutting or traction**.

Cutting Ability and Sectility

The cutting action occurs at the **resection port**, where the tissue is presented to the cutting edge. The resection port may or may not be identical with the **aspiration port**, that is, the narrowest site in the aspiration system which may be occluded by aspirated tissue.

For *cutting* the tissue is divided by a **punch mechanism** which requires that the cutting edges meet for their full length under uniform pressure.[54]

Only motions accross the resection port are effective for cutting. Blade excursions beyond the aperture may merely cause side-effects because in case of insufficient sharpness the blade pulls undivided fibers that transmit traction to surrounding tissue. The length of blade excursions, therefore, is critical in instrument design: *Rotary* actions have an infinitely long travel and consequently pose high risks. By contrast, the amplitudes of an *oscillating* or "chopping" action – whether about the central axis (Fig. 2.87-1) or along the axis (Fig. 2.87-2) – can be kept at a minimum.
For *immobilisation* of the tissue in front of the cutting edge either aspiration by occlusion, enclosure, or inertia can be used. **Aspiration by occlusion** is suitable if the substrate is sufficiently compliant (Fig. 2.88).[55] Here the aspiration can serve further to increase the sharpness of the cutting action: In instruments whose cutting edge passes directly over the aspiration port, so that the aspiration port and the resection port are identical (Fig. 2.88a), the suction makes the tissue tense as it is presented to the cutting edge and thus improves its sectility.

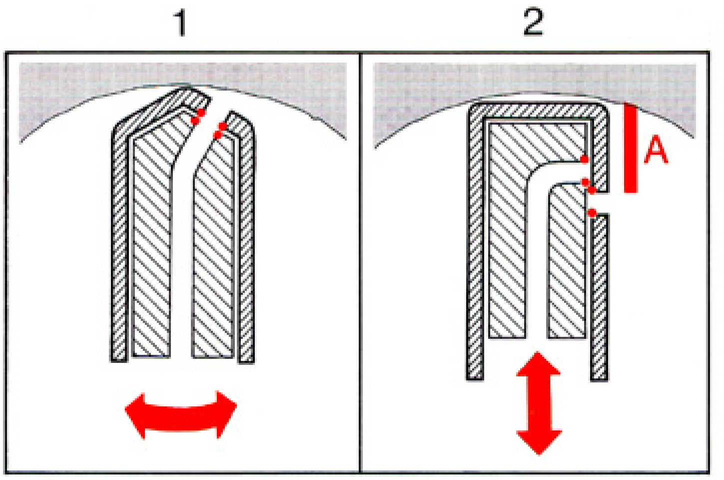


Fig. 2.87. **Position of the inlet in suction cutters**
Left: In rotary-action cutters, the inlet can be located close to the tip. This makes it possible to cut close to tissue surfaces lying *ahead of* the tip.
Right: Cutters with a reciprocating action have a side opening placed some distance back from the tip. The minimum distance *A* depends on the amplitude of the cutting motion

◄———

Fig. 2.86. **Suction cutting instruments**
Column 1: Instruments with a rotary cutting action (continuous or oscillating).
Column 2: Instruments with a reciprocating (axial) cutting action.
Row a: Instruments in which the resection port and aspiration port are the same ("sipping" action).
Row b: Instruments in which the resection port is separated from the aspiration port by an antechamber ("nibbling" action).
Row c: High-frequency vibrators (emulsifiers).
Red: Cutting edges

[53] Due to the short and rapid travel the movements of the blade are invisible.
[54] This mechanism is entirely different from the scissors mechanism in which the blades meet at a single point and, by their relative movements, drive the cutting point forward (see Fig. 2.77). Full edge-to-edge contact requires precision engineering. Instruments whose resection port is *at the front of the tip* pose the fewest technical problems (Fig. 2.86-1) since the cutting edge can be pressed forward against the opposing edge by a spring mechanism. Any frictional wear is advantageous as it improves the pressure and contact between the edges. In *side-cutting* instruments (Fig. 2.86-2) it is more difficult to press the cutting edges together by active force, and wear degrades the contact between the edges over time.
[55] Note: In this technique the aspiration port is occluded by the material to be aspirated, so there is no danger of inadvertent aspiration of neighboring tissue.

back to index

Immobilisation by enclosure is used for tissue that will not occlude the aspiration port because of its firm consistency. For this purpose, instruments are used in which the aspiration port and the resection port are separated by an *antechamber* (Fig. 2.86b). The geometry of the antechamber is such that material introduced into the chamber cannot evade the cutting edge (Fig. 2.89). Here, suction does not contribute to grasping the tissue.[56] Also suction does not increase tissue tension. The only way then to improve the sharpness of the cutting process is to increase the speed of the cutting motion. *Note*: The critical factor is the speed of the individual stroke, which does not necessarily correlate with the cutting frequency.[57]

Immobilisation by inertia: The principle of high-speed cutting finds its extreme application in *ultrasonic vibrators*. These instruments operate at such high speed that the tissue is held in place for cutting purely by its own *inertia*. The effective "sharpness" of the cutter depends critically on speed, so much so that the characteristics of the cutting edge are of minor importance. There is not even a need for an opposing edge, so the ultrasonic vibrator may consist of a simple open tube.

The appropriate *excursion* of the vibrator tip depends on the mass of the tissue to be resected. If the excursion is too small, the cutting action is poor. If too large, only a portion of the applied energy goes into dividing the tissue; another portion produces concomitant movements of the particle, which may even be transmitted to the environment. Therefore, as the tissue mass is debulked during the procedure, the tip excursions should be reduced accordingly so that the tissue continues to be divided rather than shaken.

Because part of the applied energy is converted to heat, continuous **cooling irrigation** should be maintained to avoid damage to surrounding tissues. This complicates volume regulation and makes the chamber more susceptible to the effects of external forces (see Fig. 1.5c and 1.7).

The Control of Cutting and Traction

Whether cutting or traction shall predominate in the instruments action depends on the relation between *frequency* and *suction*.

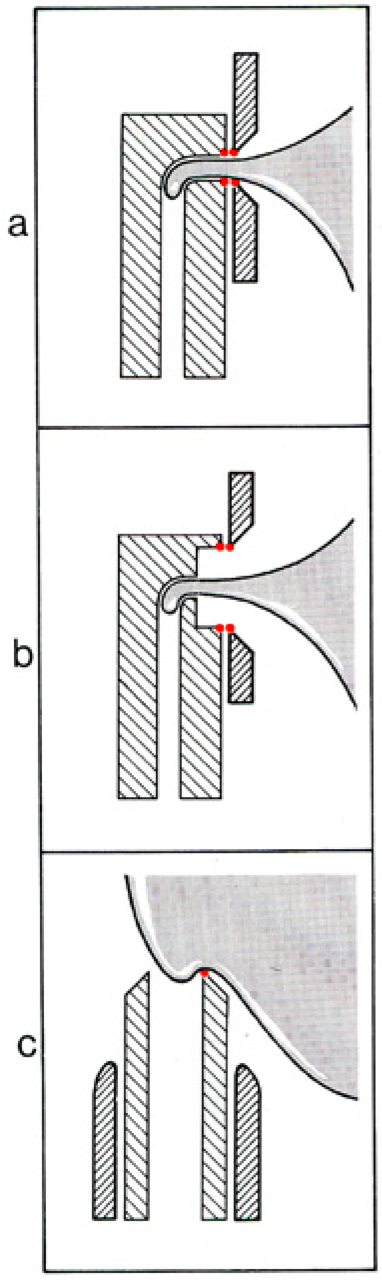
For a given level of suction, the frequency of the cutting motion determines the tissue volume that is resected per operating cycle. **Changes in the cutting frequency**, therefore, may require a **modification of the suction**. If the suction is too **high** relative to the cutting frequency, too much tissue is drawn into the tip before it is divided, and the instrument mainly exerts traction on surrounding structures. If the suction is too low relative to the cutting frequency, there will be insufficient time to present enough tissue to the cutting edge, and the instrument will have no effect. Therefore, the **rules for regulating the cutting frequency** at a given force of suction are: If the goal is to *avoid* any traction on tissues,[58] the cutting frequency should be high initially and gradually reduced until a visible cutting action is obtained. But if the tactical goal is traction,[59] one should start with a low frequency, observe the effect, and begin cutting only when it is appropriate to discontinue the traction.[60]

The main danger in the use of suction cutters is unplanned traction because this may act on surrounding tissue and cause damage at unexpected sites. The *general safety strategy*, then, aims at preventing unplanned traction altogether and minimizing the consequences in case it should occur in spite of all precautions. This means:

- instrument **design** with short travel of blade
- instrument **setting** with high cutting frequency at the beginning and decreasing gradually depending on the requirements of a specific situation
- instrument **position** at sufficient distance from critical areas because side-effects will be noted only after they have occurred.

[56] This applies to "nonoccluding" material. Compliant tissue will be sucked into the tip despite the presence of an antechamber. Here aspiration serves mainly to deform the tissue so that it will fit through the antechamber.
[57] Even with a low frequency, the individual stroke may be very fast.
[58] E.g., in a vitrectomy.
[59] E.g., for the removal of cataractous lens matter.
[60] The problems related to ultrasonic vibrators will be described in chapter 8.3.3.

back to index



2.88

Fig. 2.88. **Grasping of pliable material**

a Aspiration by occlusion: Tissue fibers are drawn into the aspiration port and are simultaneously made tense for sectioning by the cutting edge. Sectility, then, can be improved by increasing the suction.

b In cutters with an antechamber, the site where the tissue is grasped (aspiration by occlusion at the narrowest diameter) is separated from the cutting edge. As a result, tissue tension at the aspiration port does not provide effective tension at the resection port, and sectility is not enhanced by increasing the suction.

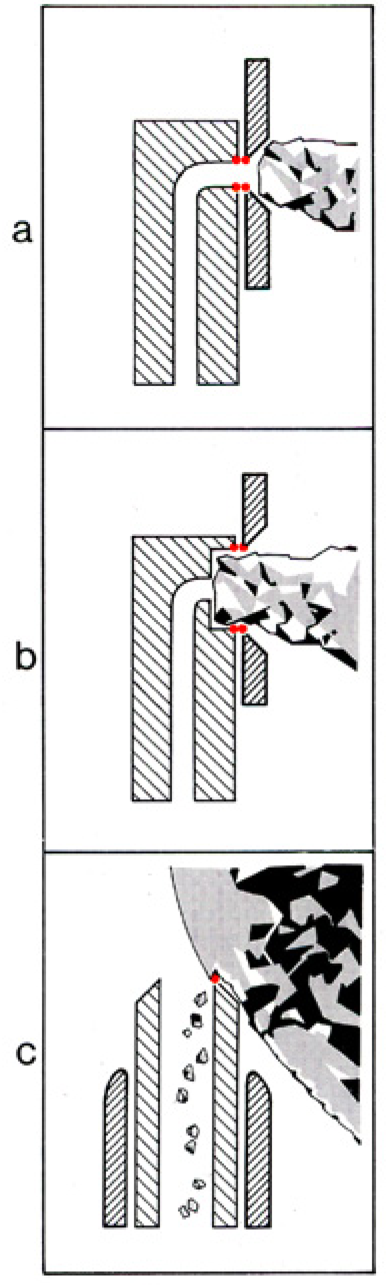
c Ultrasonic vibrators are ineffective on material having a high compliance and low mass, because the vibrating tip will push the tissue aside rather than cut it

Fig. 2.89. **Grasping of rigid material**

a Aspiration by occlusion is ineffective for grasping rigid material, for the latter cannot conform to the aspiration opening. Thus, the instrument cannot cut material whose cross-section is greater than that of the aspiration port.

b Instruments with an antechamber can cut tissue that fits into the chamber. *Note*: Suction does not improve the grasping effect. It only increases the risk of inadvertent aspiration of surrounding tissue because the suction port is not occluded.

c High-frequency vibrators are effective cutting instruments on firm material whose inertia keeps it from being pushed aside



2.89

back to index

Needles

Needles consist of a cutting component (*head*) which forms the suture track, a handle (*shaft*) by which the needle is held, and an *eye* through which the suture material is passed (Fig. 2.90).

The **cross-section of the needle track** depends on the *arrangement of the cutting edges*, each of which cuts its own path through the tissue (Fig. 2.91). Thus, a *three-edge* head makes three cuts, each in the direction of the corresponding preferential path. A *two-edge* head makes two cuts on the same plane. A *round-bodied* (edgeless) needle tears a channel through the tissue. Needles whose heads have a larger cross-section than the parts that follow produce a large-diameter track and decrease the resistance to passage of the shaft and thread.

The **longitudinal profile of the needle track** corresponds to the *path of the needle tip*. Being a geometric point, the needle tip can in theory be guided in any direction. But in practice its mobility is limited by lateral resistance, which varies with the configuration of the preferential

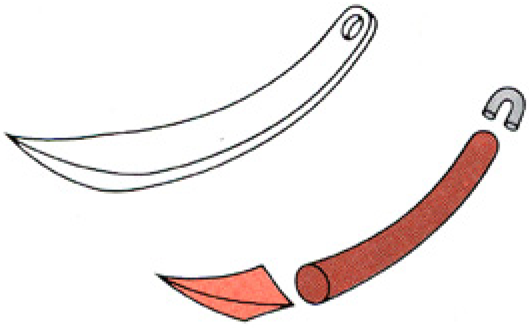


Fig. 2.90. **The parts of a needle**. A surgical needle consists of a head (pointed tip and lateral cutting edges), shaft, and eye

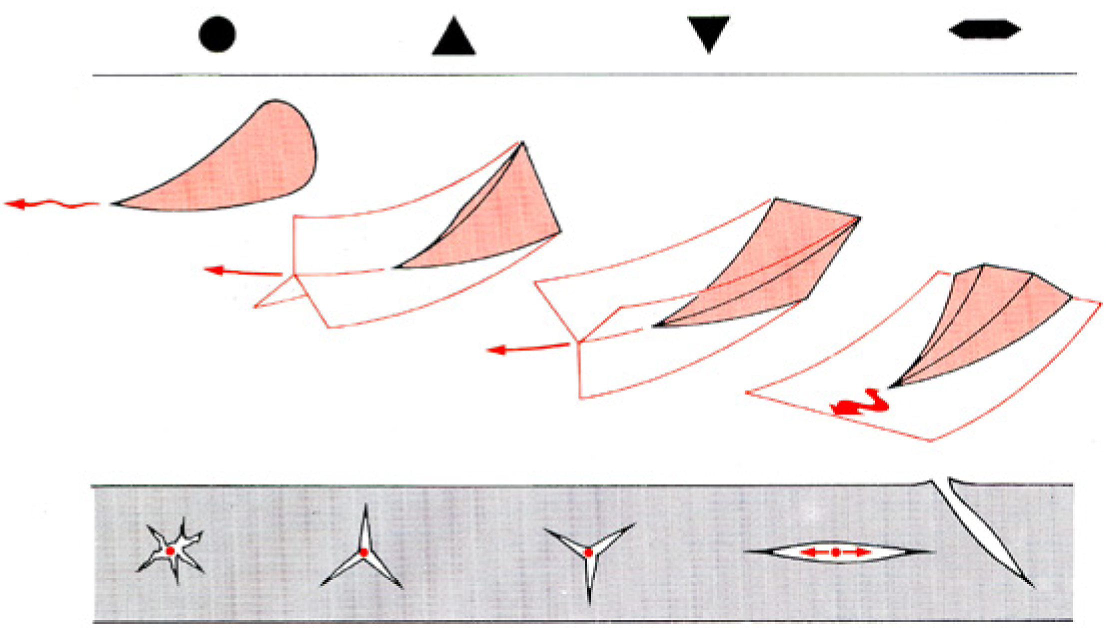


Fig. 2.91. **Shapes of needle heads**. The arrangement of the lateral cutting edges and their preferential paths determine the cross-sectional shape of the needle track.

Top row: Cross-section of needle head.
Middle row: Three-dimensional drawing of head with the preferential paths (red outline).
Bottom row: Cross-section of resulting needle tracks. Red dot corresponds to the position of tip and thus to the surgeon's intent.

Round heads (*left*) penetrate tissue by blunt dissection. The cross-section of the track follows tissue interspaces of least resistance.
Heads with three cutting edges (*center*) have three lateral preferential paths and cut a track with a Y-shaped cross-section. The cross-section of the track may extend upward (*center left*) or downward from the center of the Y (*center right*) depending on the position of the vertical edge. The three-dimensional arrangement of the preferential paths creates lateral resistances that stabilize needle guidance.
Heads with two cutting edges (*right*) form a slitlike track whose central axis corresponds to the path of the needle point. The preferential paths of the two cutting edges are congruent, so there is relatively little resistance to lateral deviations. This type of needle head can easily lacerate the tissue (*right*) unless it is guided strictly parallel to the tissue surface (*left*)

back to index

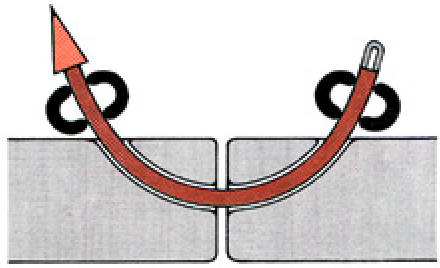
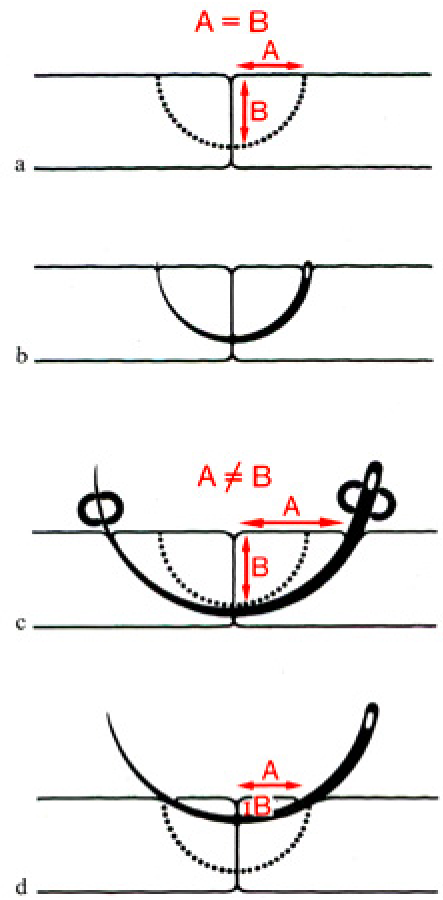


Fig. 2.92. **Length of the shaft.** To preserve the delicate head and eye, the needle is gripped *only* by its shaft or "handle." The shaft must be long enough to be grasped by the needleholder (*black*) during insertion and emergence of the needle



paths of the lateral edges (Fig. 2.91) and with the shape of the shaft.

Lateral resistance is lowest when the path of the needle tip precisely follows the curvature of the shaft, i.e., when the needle shape is perfectly congruent with the planned suture track (Fig. 2.93a, b). In practice, the shaft must be somewhat longer than the suture track so that it can be easily grasped by the needleholder during suturing (Fig. 2.92). The effect of this incongruity is increased lateral resistance when the shaft is passed through the tissue, causing deformation of the tissue or the needle (Fig. 2.94). This places correspondingly high demands on needle stability: the greater the incongruity between the needle and the suture track, the higher the tissue resistance, and the more stable the needle must be. Conversely, the finer the needle, the more closely its shape should conform to the planned suture track (Fig. 2.95).

The optimum shape of the **eye** depends on the thickness of the suture material (Fig. 2.96), since the addition of the thread diameter should not significantly increase the total cross-section. The extremely fine threads used in microsurgery pose no problem in this regard, so the advantage of "atraumatic" sutures lies more in their convenience (no threading) than in a true technical superiority.

Fig. 2.93. **Problem of incongruity between the needle shape and proposed suture tract**

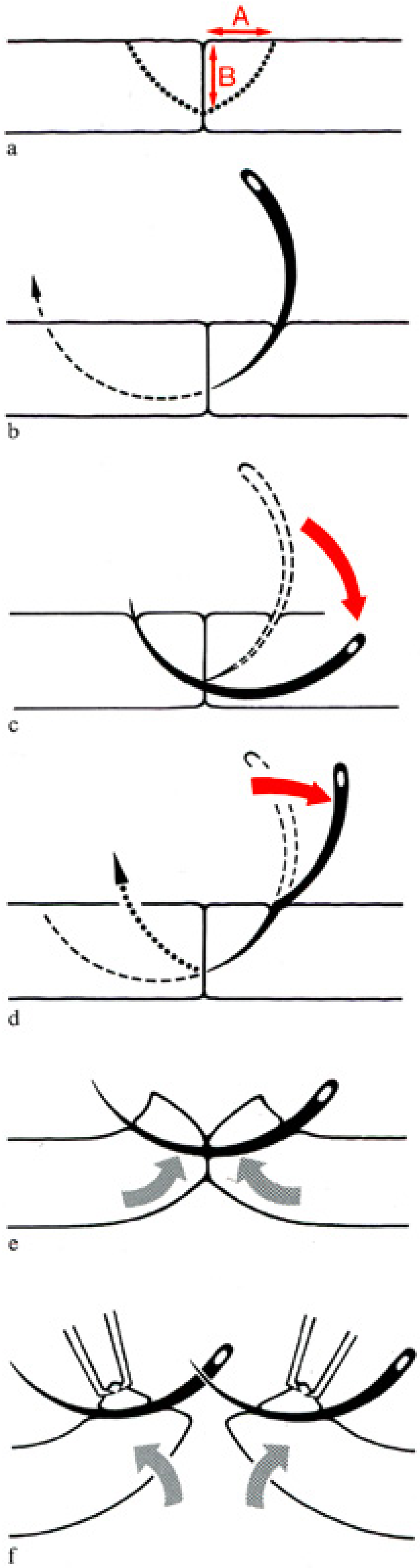
a The proposed suture tract is semicircular, i.e., the distance from the wound edge (*A*) equals the suture depth (*B*).

b A needle perfectly congruent to the planned suture tract cannot be inserted completely nor withdrawn with a needleholder.

c A needle can be grasped only if it is longer than the tract. But then the radius of curvature is also increased. If this needle is inserted to the planned depth (*B*), the bites will be longer than intended (*A*).

d If the same needle is inserted and withdrawn at the planned distances from the wound margin (*A*), the track will be more superficial than intended (*B*)

back to index



2.94

Fig. 2.94. **Solving the incongruity problem**

a The proposed semicircular track is most closely approximated by two segments of flatter curvature that are made by inserting and withdrawing a longer needle at the planned entrance and exit sites in each wound lip.

b If the needle were allowed to follow its preferential path after insertion in the first wound lip it would emerge too far from the wound line at the second wound lip.

c This is avoided by tipping the needle backward before passing it up through the second wound margin.

d If the needle is not strong enough, it will bend when this maneuver is attempted.

e If the needle can overcome the tissue resistance, the wound margins will deform instead of the needle.

f As a compromise, the needle can be passed in two steps: It is brought out through the first wound surface and then reinserted into the opposing wound surface. So rigid tissue is not deformed by the needle itself, but is bent manually with a strong grasping forceps. The difficulty in this procedure is to find the proper insertion site in the opposing wound surface

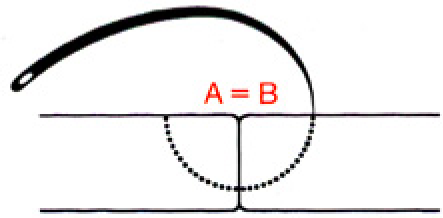


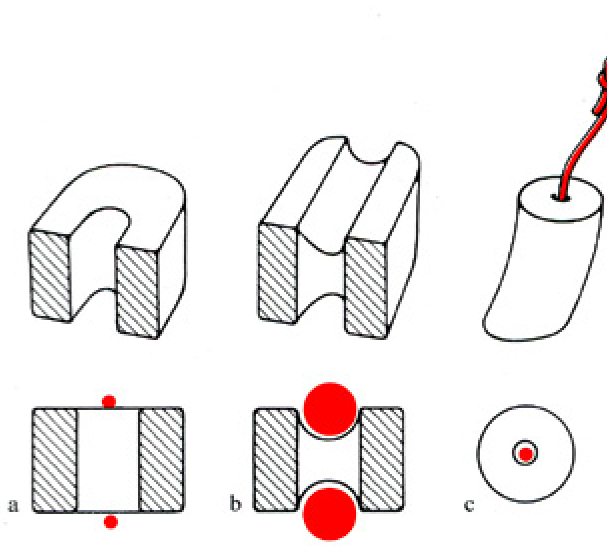
Fig. 2.95. **Compound circle needle.** The tip has a smaller radius than the shaft. Its shape is closer to that of the proposed track, so the deforming forces on the needle and tissue are reduced. Once the track has been cut with the heavily curved tip, the shaft, with its gradually increasing radius of curvature, will slip through. Increasing deformation of the tissue is inevitable at this stage, but it occurs gradually

Fig. 2.96. **The needle eye and thread diameter**

a *Simple eye* is suitable for thin suture material that adds little to the total cross section (*bottom*).

b *Recessed eye* reduces the total cross section when heavy suture material is used.

c In *atraumatic sutures*, the thread is swaged onto the end of an eyeless needle. If the thread is much thinner than the needle, even a knot can pass through the needle track. This makes it possible, in case of suture breakage, to tie a short strand on the atraumatic needle to a new thread



2.96

2.1.4 Uniting of Tissues

Functions of Sutures

The uniting of tissues by biologic processes such as scar formation is comparable to gluing with a slow-setting adhesive. The surgical uniting of an incision strives to maintain apposition of the wound edges until the "glue" has set, i.e., until the scar has attained sufficient strength.[61]

The **fixation** for this purpose must:
- hold the surfaces to be united in their correct position (*apposition*);
- press the surfaces firmly together to minimize the space that must be bridged by scar tissue (*compression*);
- *retain* the united surfaces in their apposed and compressed state, even when external forces (tension, shear) are applied.

When compression is provided by external forces,[62] the only purpose of sutures is to effect **apposition** (Fig. 2.97). Any type of stitch can give satisfactory apposition, provided the length of the stitch equals the length of the intramural suture track plus the overbridging segment. If **compression** must be effected by the suture itself (Fig. 2.98), apposition becomes problematic because compression sutures invariably cause some tissue deformation.

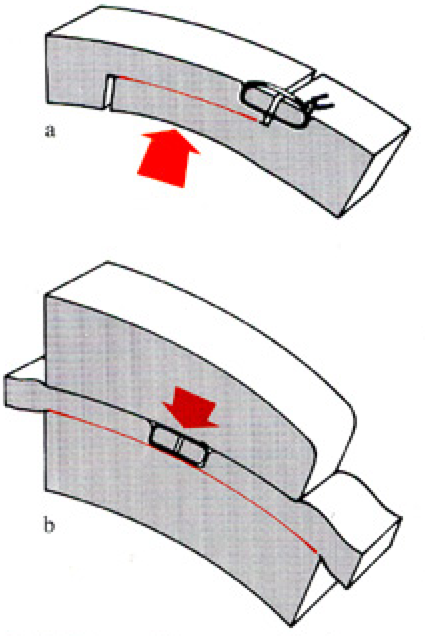


Fig. 2.97. **Apposition sutures.** Simple apposition sutures coapt the wound edges and maintain their position by splinting, but wound compression is effected by endogenous forces (compression zone: *Red*).

a *Intraocular pressure* maintains compression between the surfaces of a stepped incision.

b *Eyelid pressure* presses the conjunctiva against the surface of the sclera

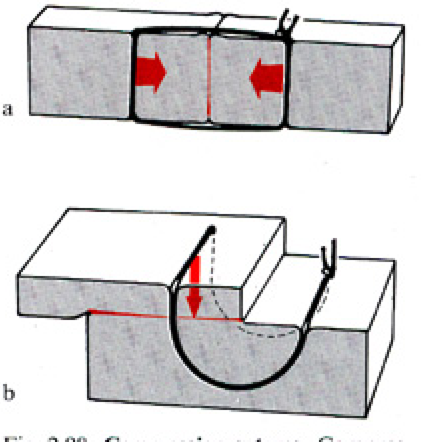


Fig. 2.98. **Compression sutures.** Compression is effected by the suture itself (compression zone: *Red*).

a A *simple interrupted suture* presses the wound margins together.

b A *mattress suture* tacks a thin tissue layer onto a firm substrate

[61] The requirements of the surgical joining technique are thus determined by the speed of the "setting" process. When a quick-setting tissue adhesive is used, it is sufficient to press the wound margins together briefly with a forceps. If definitive closure relies on scar formation, techniques must be used to retain the apposing "instrument" in the tissue for a sufficient length of time. Long-lasting sutures are particularly useful in poorly healing tissue, i.e., tissue that is poorly perfused due to its anatomy (avascular ocular tissue), surgical trauma (diathermy, excessive suture tension), or the presence of obstructions (foreign matter embedded in the wound, etc.).

[62] Endogenous forces (e.g., intraocular pressure, lid pressure) or external devices (e.g., contact lenses).

back to index

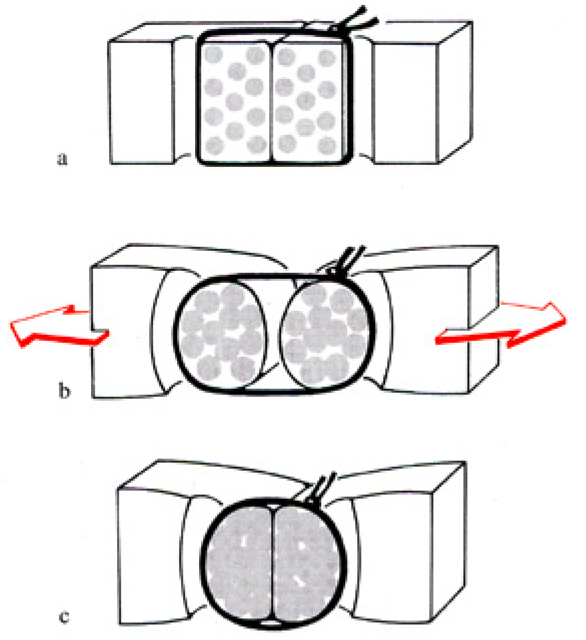


Fig. 2.99. **Mode of action of compression sutures**

a If the suture is exactly the length of the suture tract (and overlying tissue segment), it gives satisfactory apposition.

b Dehiscent traction on the wound margins may then open the wound, since the tissue encircled by the loop is compressible.

c The compression suture is effective when it places sufficient primary compression on the enclosed tissue that the latter can no longer yield to external forces

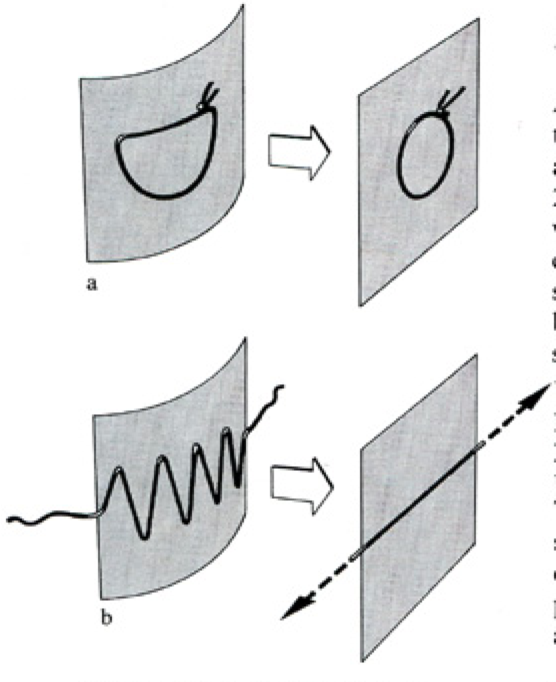


Fig. 2.100. **Rule of suture tightening**

a A simple interrupted suture tends to assume a circular shape when tightened.

b A continuous suture tends toward the shape of a straight line. *Note*: Both forms tend to lie on one plane

Tissue Deformation by Compression Sutures

A suture that causes no deformation of the untouched wound, i.e. a *simple apposition suture* (Fig. 2.99a), cannot effectively maintain wound closure under the action of external forces. The encircled tissue, being compliant, is compressed by the forces, and the wound edges separate (Fig. 2.99b). But if the suture exerts sufficient primary compression, the tissue will no longer yield to external forces, and apposition will be maintained (Fig. 2.99c). The necessary amount of compression ("*adequate compression*") thus depends on the strength of the applied forces that are anticipated in a given clinical situation.

As a suture is tightened to produce compression, the loop of suture material becomes shortened. This alters the original shape of the stitch in a way that can be predicted from the **rule of suture tightening**:

Simple interrupted sutures tend to assume a circular shape when tightened, while continuous sutures tend toward the shape of a straight line (Fig. 2.100).

As the suture becomes deformed, so does the surrounding tissue. Compression sutures always deform the entire wound area in accordance with the type of stitch that is used:

- *simple interrupted sutures* always produce inversion of the wound edges (Fig. 2.101);
- *interrupted mattress sutures* may produce inversion or eversion (Fig. 2.102);
- *continuous sutures* flatten a convex wound area (e.g., the corneal dome), and they straighten out curved incisions (Fig. 2.103). They will deform the surface when the stitches are placed irregularly, i.e at unequal distances from the wound line or at unequal depths (Fig. 2.104).

These types of deformation are a byproduct of suture compression and are unavoidable whenever such compression is required. Where possible, then, it is preferable to effect wound closure without the use of compression sutures. In planned operations it is advantageous to employ incisions that can be ade-

back to index

❮ ❯

a

b

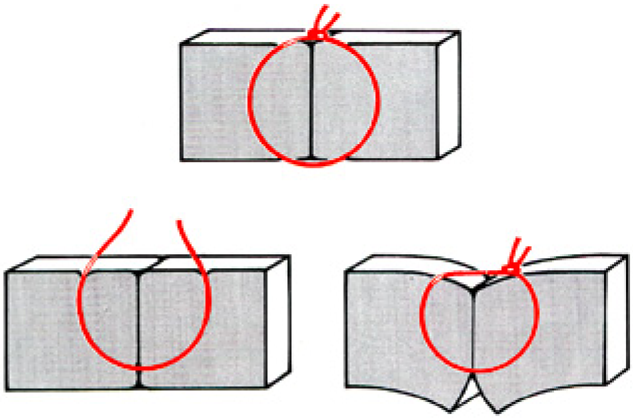


Fig. 2.101. **Tissue deformation by a tightened simple suture**

a The "ideal" suture has a circular shape from the outset and causes very little tissue deformation when tightened.

b Semicircular sutures (*left*) shorten all distances in the enclosed tissue, causing the non-enclosed portion of the wound to gape (*right*)

a

b

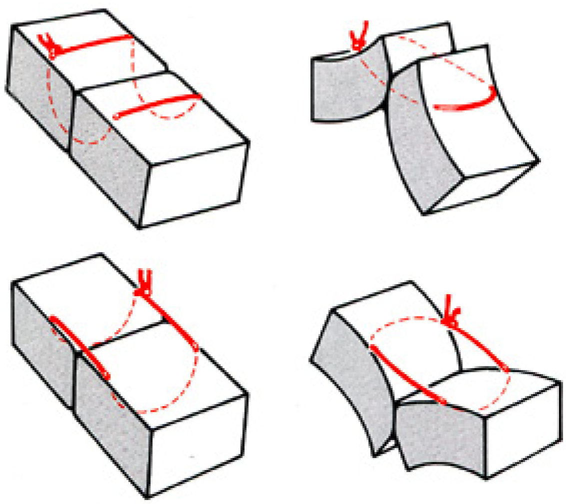


Fig. 2.102. **Tissue deformation by tightened mattress sutures**. Mattress sutures tend toward the shape of a horizontal circle when tightened. Accordingly, the intramural part of the suture is raised while the bridging segment is lowered. This either everts **(a)** or inverts the wound margins **(b)** as all parts of the loop move onto the same circular plane

a

b

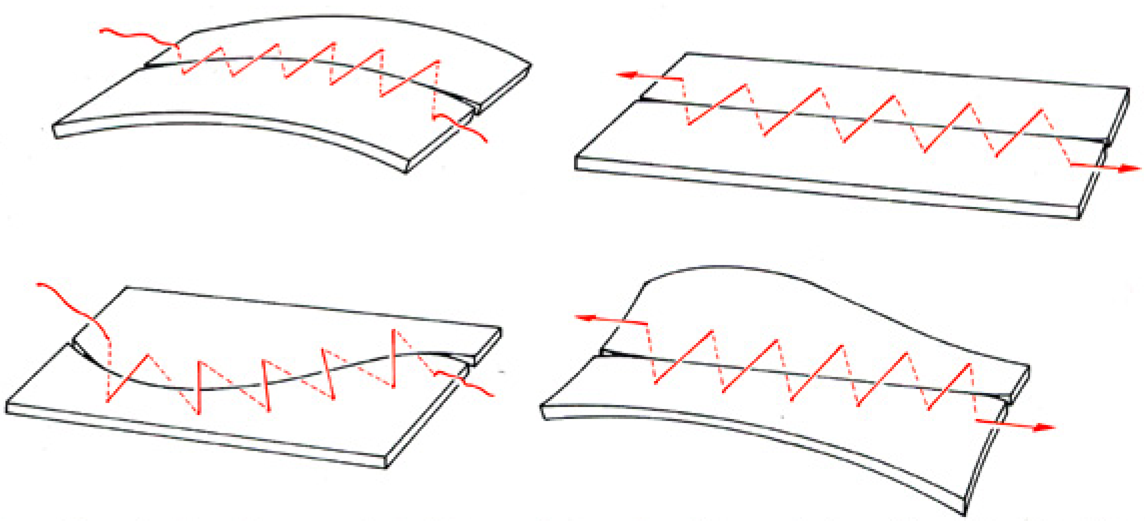


Fig. 2.103. **Tissue deformation by a tightened continuous suture**

Left: Loose suture.
Right: Tight suture.

a Arched tissue surfaces tend to flatten when the suture line is tightened.

b A curved wound line is straightened, accompanied by torsion of the surrounding tissue

back to index

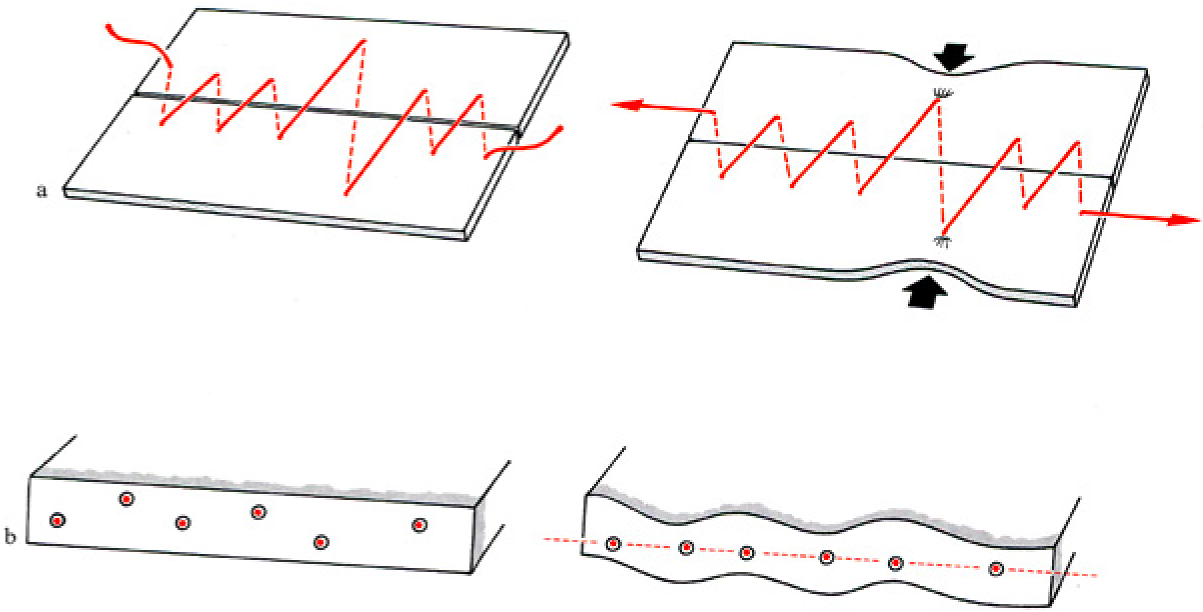


Fig. 2.104. **Tissue deformation by irregularly placed continuous sutures**

a Bites at irregular distances from wound: When the continuous suture tends towards a straight line on tightening, the surrounding tissue is more compressed at the larger bites than at the shorter ones.

b Bites at irregular depths: If the suture tracts occupy different levels on the wound surface, they move onto one plane when the thread is tightened. The surrounding tissue is correspondingly raised or depressed, and the tissue surface becomes irregular

quately closed with simple apposition sutures, i.e., incisions in which other forces can be utilized to compress the wound margins (see Fig. 2.97). In situations where there is no alternative to the use of compression sutures, the optimum stitch is that which will supply the necessary compression with a minimum of side-effects, i.e.,

- a stitch that requires minimal "overcompression" to produce adequate compression along the wound line;
- a stitch whose force vectors produce maximum compressing vector components with a minimum of vectors in other directions.

These concepts will be discussed more fully below.

Force Vectors of Sutures

In technology, compression is effected by means of press or clamp mechanisms that apply the necessary force vectors in an optimum direction (Fig. 2.105a). By contrast, the sutures employed by surgeons always produce *vector components acting in various directions*, some of which do not contribute to wound compression and can actually undermine it (side-effects, see Fig. 2.105b).

The *force vectors* produced by suture tightening can be resolved into three components:

The component that *compresses* the wound margins is directed **perpendicular** *to the* **wound** *surface* (Fig. 2.106). The compressed portion of the wound is the projection of the intramural part of the suture onto the wound surface. If the intramural suture segment is placed *perpendicular* to the wound surface, the compressing vectors are all on the plane of that segment, and the compressed portion of the wound is a *line* – the line where the suture plane intersects the wound surface (Fig. 2.106a). If the intramural segment crosses the wound *obliquely*, its projection onto the wound surface is an *area* (Fig. 2.106b).

The vector component **parallel** *to the wound margin* (Fig. 2.107) tends to *shift* the wound surfaces laterally. It is produced by all sutures that cross the wound obliquely. In *simple interrupted sutures* the shifting vector is incompatible with perfect

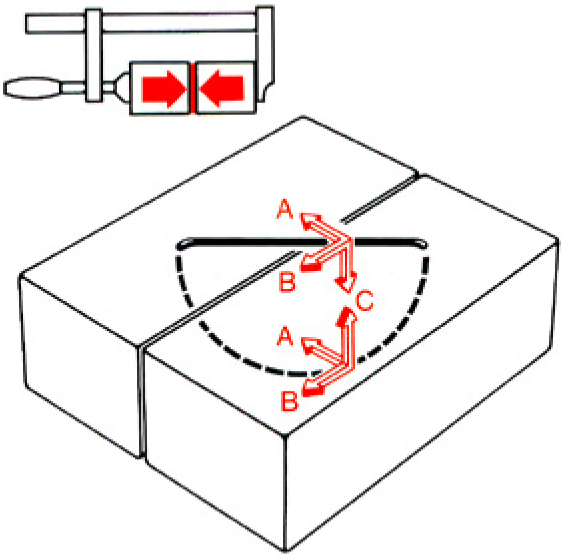


Fig. 2.105. **Force vectors of compressing instruments**

a In technology, compression is effected by tools that produce purely compressive vector components (i.e., perpendicular to the surfaces being compressed).

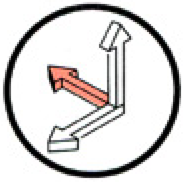
b Sutures produce three vector components:
A Perpendicular to the wound margin: Compressing vectors.
B Parallel to the wound margin: Shifting vectors.
C Perpendicular to the tissue surface: Inverting or everting vectors

wound closure, so sutures of this type should not be placed obliquely (Fig. 2.107a, b). In *continuous sutures*, on the other hand, the shifting vectors of the bridging segments can serve to neutralize the shifting vectors of the intramural segments (Fig. 2.107c).

The third vector component is **perpendicular** *to the* **tissue** *surface* (Fig. 2.108). The portion directed upward from the intramural segment tends to *evert* the wound margins, while the portion directed downward from the bridging segment tends to *invert* them. If both segments are on the same plane, as in a *simple interrupted suture*, both components cancel out (Fig. 2.108a). *Continuous sutures*, on the other hand, include successive inverting and everting segments that can produce irregularities in the tissue surface (Fig. 2.108b). This is avoided by placing the loops very close together so that the everting and inverting components are on approximately the same plane (Fig. 2.113).

The effect of these vectors on the tissue is complicated by the fact that the *tissue resistances* opposing the vectors are different in the intramural and bridging segments of the suture. The tensile forces of the *bridging segments* act only at the entry and exit sites of the thread and encounter no tissue resistance. By contrast, the vectors of the *intramural segments* act directly on the tissue, where they are exposed to and limited by tissue resistance. This means that the side-effects of the bridging segments tend to be greater and the desired effects less than in the intramural segments of the suture.

back to index



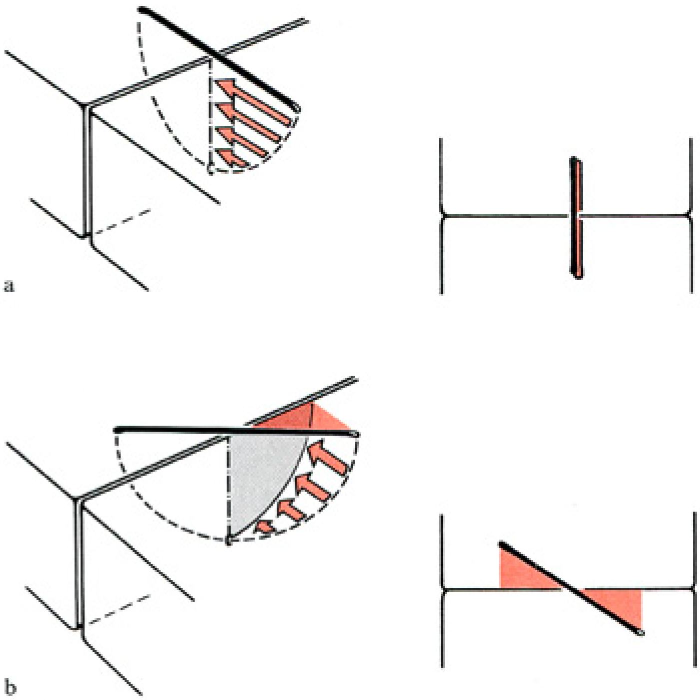
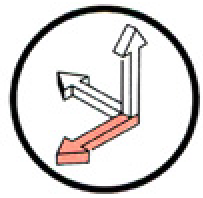


Fig. 2.106. **The vectors of wound compression**
Left: Perspective drawing.
Right: Overhead view of the tissue surface (used in subsequent figures to demonstrate the compressive properties of different stitches).

a With a simple interrupted suture placed perpendicular to the wound line, all the compressing vectors are on one plane. Wound compression occurs on the line where that plane intersects the wound surface. The overhead view (*right*) shows the upward projection of the compressed zone, which is a line.

b With a simple interrupted suture placed oblique to the wound line, the compressing vectors occupy a three-dimensional space between the intramural parts of the suture and the wound surface. The zone of compression at the wound surface is an area. The perspective view (*left*) shows the three-dimensional character of the compression. The overhead view (*right*) shows the compression zone projected onto the tissue surface



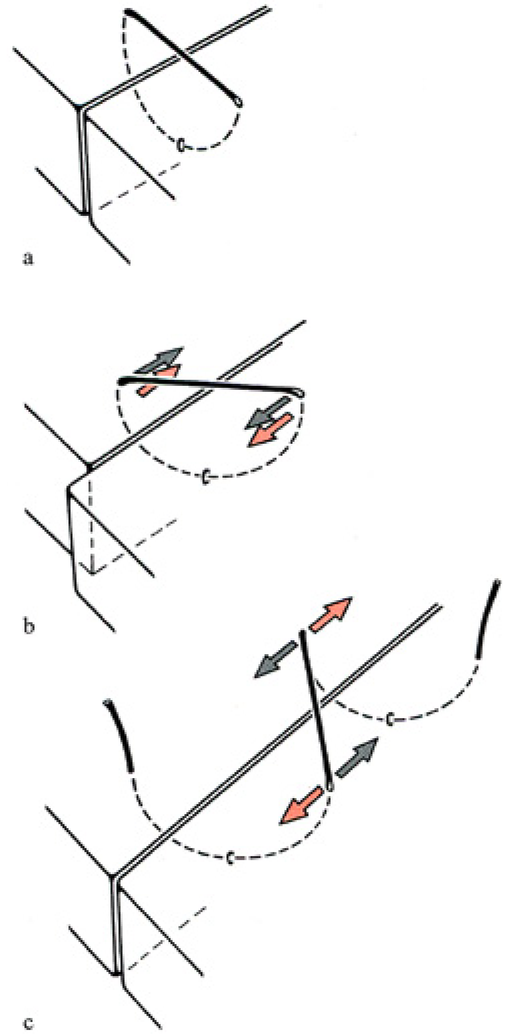


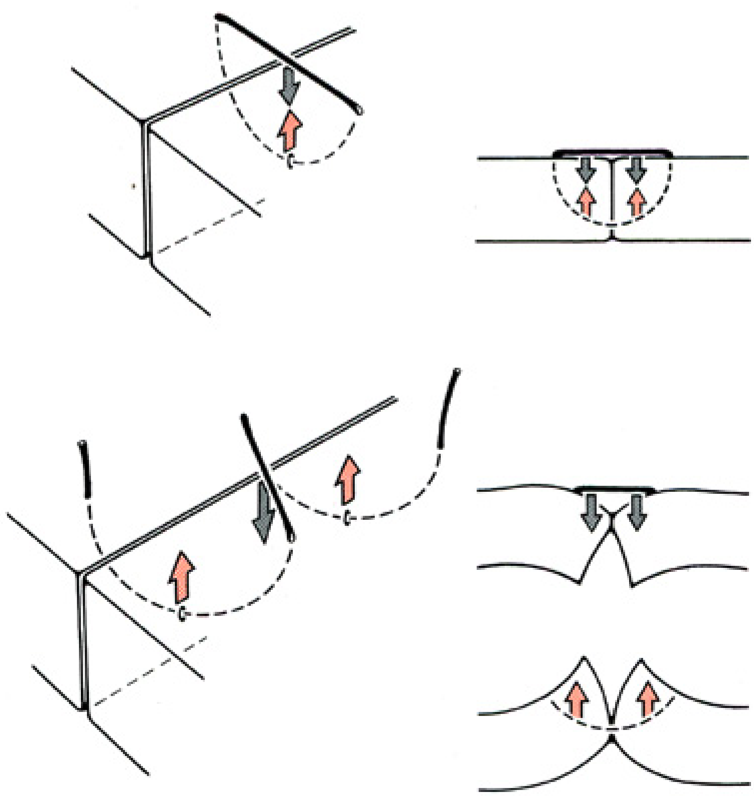
Fig. 2.107. **Vectors of lateral shift**

a Simple interrupted sutures perpendicular to the wound line cause no lateral shift.

b An oblique suture gives rise to shifting vectors. These vectors are equidirectional for the intramural and bridging parts of the suture, so a substantial lateral shift is produced.

c In continuous sutures, the shifting vectors of the intramural and bridging segments are not necessarily equidirectional. They may act in opposite directions and cancel out

back to index



a

b

Fig. 2.108. **Vectors perpendicular to the tissue surface**

a In the simple interrupted suture, the perpendicular vectors in the bridging segment (downward directed) and intramural segment (upward directed) are on the same plane, so they cancel out.

b In the continuous suture, the perpendicular everting and inverting vectors are on different planes (*left*). The inverting action of the bridging segment (*upper right*) and the everting action of the intramural segment (*lower right*) deform the tissue level accordingly, producing alternate areas of inversion and eversion along the wound line

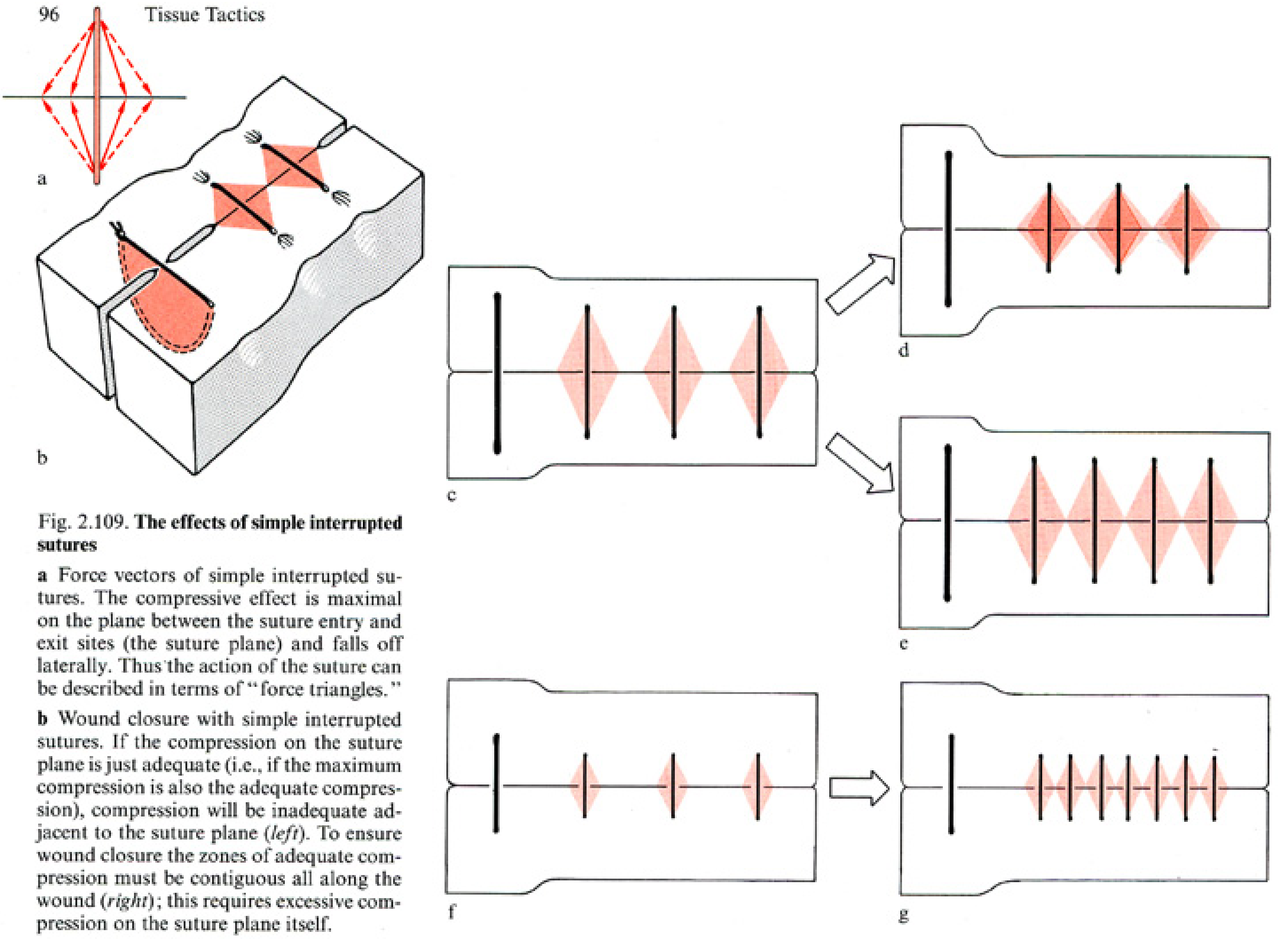


Fig. 2.109. **The effects of simple interrupted sutures**

a Force vectors of simple interrupted sutures. The compressive effect is maximal on the plane between the suture entry and exit sites (the suture plane) and falls off laterally. Thus the action of the suture can be described in terms of "force triangles."

b Wound closure with simple interrupted sutures. If the compression on the suture plane is just adequate (i.e., if the maximum compression is also the adequate compression), compression will be inadequate adjacent to the suture plane (*left*). To ensure wound closure the zones of adequate compression must be contiguous all along the wound (*right*); this requires excessive compression on the suture plane itself.

c–e Wound closure with large sutures.
c Shortening the loop of a simple apposition suture (*left*) widens the compression triangles (*right*). But the zones of adequate compression are not contiguous in the example shown. This is achieved either by shortening the loops further or increasing the number of stitches.

d Shortening the loops further will widen the compression zones but will increase the excessive compression in the suture area.

e Increasing the number of stitches leads to contiguous zones of adequate compression without altering the strength of the compression.

f, g Wound closure with short sutures.
f Shorter loops produce narrower compression triangles than in **c**.

g Consequently the sutures must be spaced closer together than in **e**, resulting in a greater number of stitches

Characteristics of Particular Suture Types

Simple Interrupted Sutures

In simple interrupted sutures, tension is confined to the area of the individual loop of thread. Therefore, simple interrupted sutures are useful for producing a localized tension that is specifically adapted to local conditions.

The side-effects of undesired force vectors are minor in simple interrupted sutures, because the *vertical vectors* cancel out while the *shifting vectors* can be eliminated by a precise suture technique (Fig. 2.106a).[63] The effect of the *compressing vectors* is maximal in the suture plane and diminishes with distance from it (Fig. 2.109a). If the compression on this plane is just adequate, the compression immediately adjacent to the plane will be inadequate. This means that if *adequate compression* is required adjacent to the suture plane, this must be accomplished at the cost of excessive compression (*overcompression*) in the suture plane itself.

Effective wound closure is obtained when the "zones of adequate compression" are contiguous along the entire wound line (Fig. 2.109b).

[63] If we define "side-effects" as all effects other than compression, we must recognize that in some circumstances these "side" effects can be utilized to achieve specific goals (see Fig. 5.90b).

back to index

Thus, the maximum allowable **spacing** of adjacent interrupted sutures depends on the *width of the zones of adequate compression*. The width of these zones depends in turn on the amount of tissue encompassed and its degree of compression, i.e., on the diameter of the thread loops and the degree of suture tension.

The efficacy of wound closure can be improved by increasing either the number or the width of the compression zones along the wound line. Increasing the number of compression zones means increasing the number of stitches (i.e., narrowing the spacing between them), while widening the compression zones means enlarging the diameter of the thread loops.[64] The relationship that exists between the spacing of the stitches and their diameter leads to the **spacing rule for simple interrupted sutures**: Large suture loops may be spaced at longer intervals than small suture loops (Fig. 2.109e, g).

[64] In thin tissue layers such as the cornea, such options are limited by the need to make the suture loop as circular as possible (see Fig. 2.101a). Spacing the threads farther apart would cause the stitches to elongate, increasing the risk of significant inversion when the sutures are tightened.

Continuous Sutures

The loops in a continuous suture line can shift relative to one another as the suture is tightened, leading to a *uniform distribution of tension* over the encompassed area.

Because of the uniform tension, continuous sutures are excellent for situations in which forces act evenly along the wound (e.g., a rise of intraocular pressure). However, they may not protect the wound from locally applied forces (Fig. 2.110). They are appropriate for the closure of straight or circular wound lines (see Fig. 5.95), but they are poorly suited for irregularly shaped wounds that require different amounts of tension at different sites (see Fig. 5.89).

The **width of the compression zone** depends on the *obliquity* of the intramural segment. Therefore the compression zones can be made contiguous by using the appropriate type of *stitch*. The width of the compression zones can be enlarged simply by *increasing the obliquity* of the intramural segment. This means that continuous sutures can apply adequate compression with minimal overcompression.

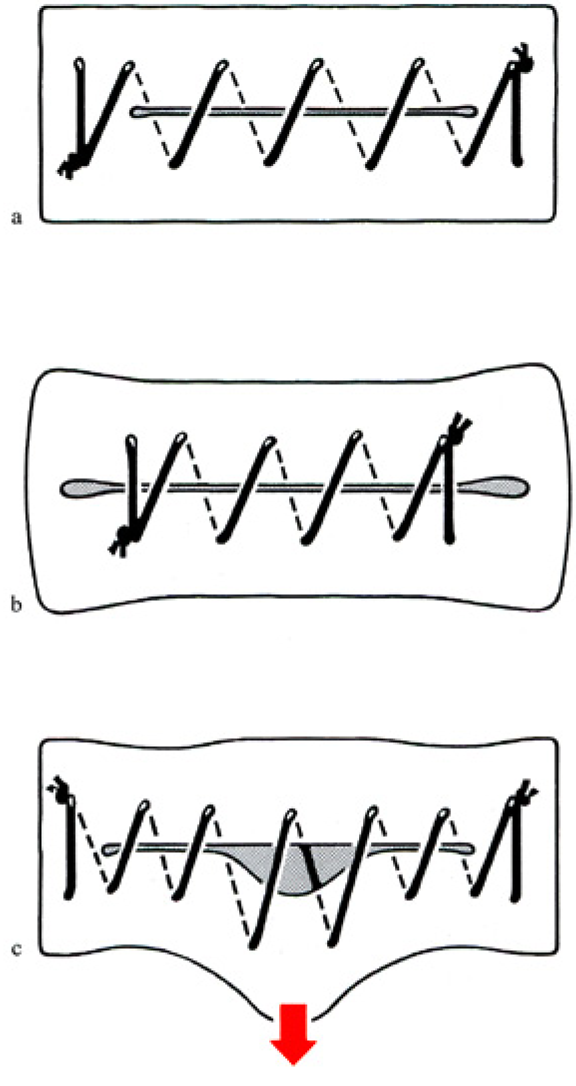


Fig. 2.110. **Mode of action of continuous sutures** ►

a Tension is evenly distributed over the entire suture line, which starts and ends beyond the ends of the wound ("in healthy tissue").

b If the ends of the wound are not encompassed by the suture, they will not be compressed.

c Balanced tension allows localized forces to open one part of the wound while adjacent parts come under increased compression

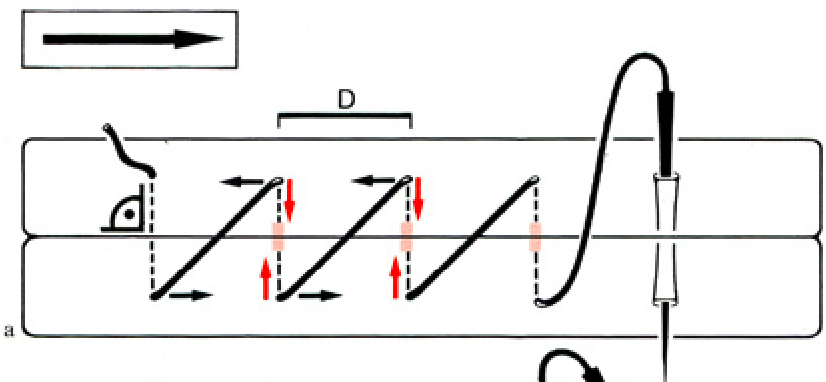
Fig. 2.111. **Compression zones and lateral shift vectors in continuous sutures**
Left: Different stitch patterns are created by changing the angle between the intramural segment and wound line (i.e., by changing the obliquity of needle insertion) while keeping a constant distance (*D*) between the stitches.
Right: Similar patterns are obtained by spacing the stitches differently but keeping the same obliquity.
Pink: Compression zones (cf. Fig. 2.106).
Black arrows: Lateral shift vectors of the bridging suture segments.
Gray arrows: Lateral shift vectors of the intramural segments (whose effect is lessened by increasing friction).

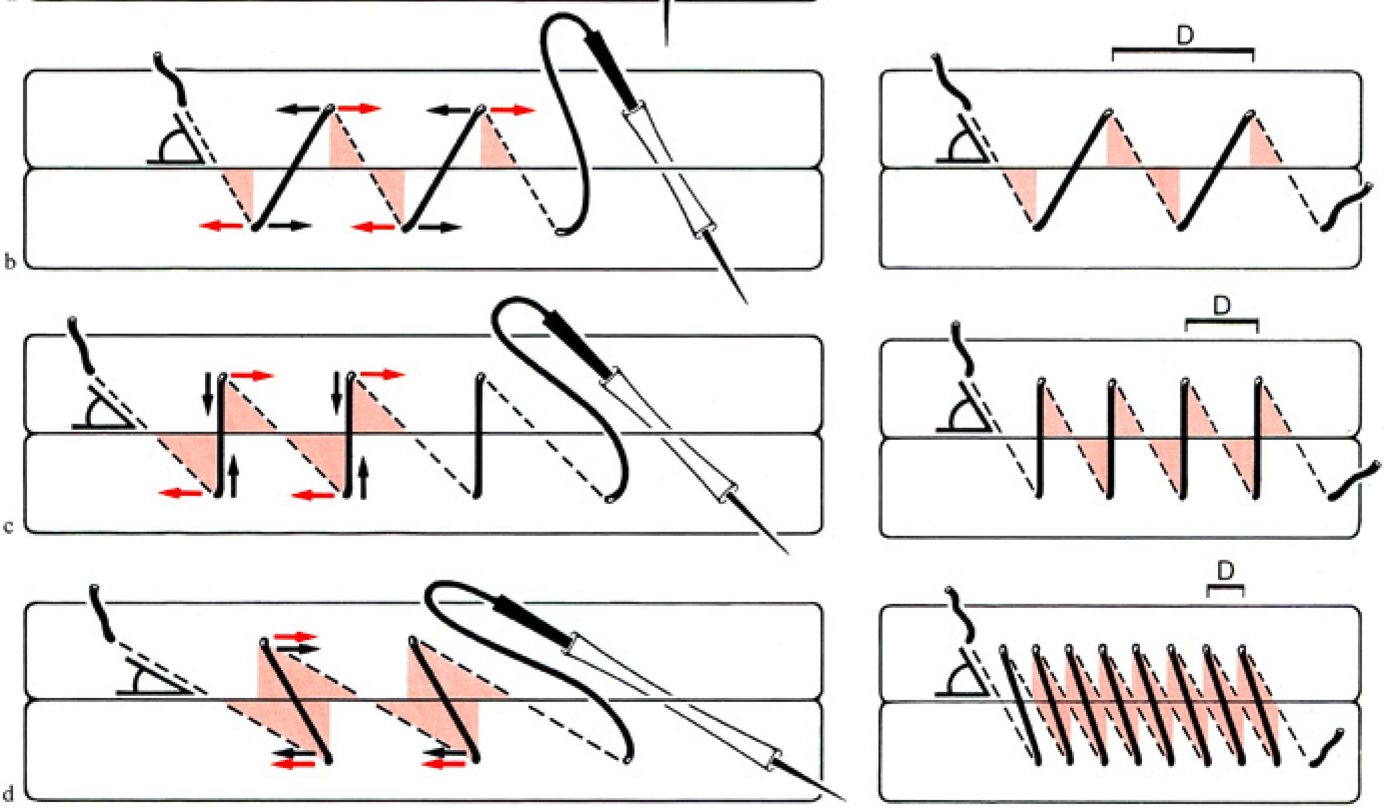
a Simple sawtooth stitch: The intramural segments are perpendicular to the wound line, and the compression zones are linear (as in simple interrupted sutures). Lateral shift vectors do not exist in the intramural segments but are very strong in the bridging segments, where they are not neutralized by opposing shift vectors or reduced by the friction of a wide compression zone. Consequently this type of suture produces a strong lateral shifting tendency when the suture line is tightened.

b Symmetrical sawtooth stitch: The intramural and bridging segments form equal but opposite angles to the wound line. The obliquity of the intramural segments determines the width of the compression zones, which are noncontiguous. In fact, the wider the compression zones, the wider the noncompressed intervals for reasons of symmetry. The lateral shift vectors of the intramural and bridging segments act in opposite directions. Though they have the same magnitude, the intramural vectors are checked by friction, so the vectors of the bridging segments predominate. There may be still a tendency toward lateral shift, therefore.

c Inverted sawtooth stitch: Here the bridging segments are perpendicular to the wound line. The compression zones of the intramural segments are contiguous and encompass the entire wound. The bridging segments, being perpendicular, have no lateral shift vectors, while those of the intramural segments are checked by friction. The result is good compression with little tendency toward lateral shift.

d Overlapping sawtooth stitch ("sharktooth" suture): Both the intramural and bridging segments are oblique to the wound line, forming angles that are equidirectional but of different size. The overlapping compression zones provide for effective wound closure. The vectors of lateral shift are equidirectional in both the intramural and bridging segments. Their "double" shifting action, however, is opposed by the increased friction produced by the "double" compressing force vectors. Also, the latter prevent the outward movement of the needle entry and exit sites that is necessary to initiate lateral shift in this type of suture





back to index

However, one **side-effect** of this increased tension is an increase in *undesired force vectors* that can alter the position of the wound margins. These vectors should be taken into account, therefore, when selecting the suture pattern. The *lateral shift vectors* acting in the direction of the bridging segments produce greater effects than those in the direction of the intramural (compressing) segments, because they are less constrained by friction between the wound surfaces. The effects of the lateral shift vectors in relation to the compression zones are analyzed for various suture patterns in Fig. 2.111.

The extent of the lateral shift for a given suture pattern is limited by the *suture spacing*. This makes it possible to reduce lateral wound shifting simply by shortening the interval between the stitches (Fig. 2.112).

Also, the effects of the *vertical vectors* are reduced by decreasing the *lateral distance* between the intramural and bridging segments (Fig. 2.113).

Thus, maximum compression with minimal side-effects can be achieved by using an overlapping sawtooth suture pattern ("shark's-tooth" suture) with closely spaced stitches. The compression zones in this suture overlap, so minimum tightening is required to secure wound closure (Fig. 2.111d). Lateral shift vectors are neutralized by friction between the wound surfaces, which increases tremendously when even slight suture tension is applied (Fig. 2.111d). Vertical vectors are neutralized by the close spacing of the stitches (Fig. 2.113).

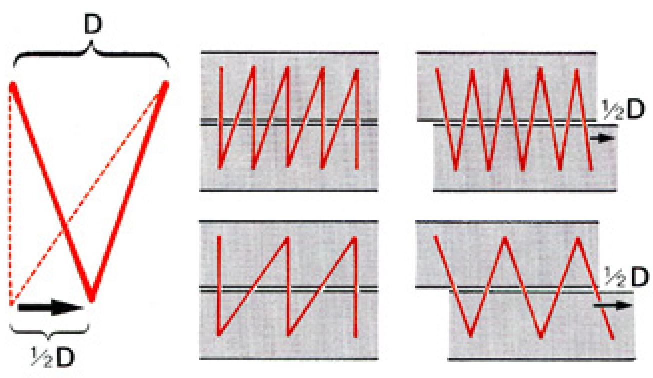


Fig. 2.112. **Relationship between lateral shift and suture spacing, illustrated for a simple sawtooth stitch.** The lateral shift necessary to produce a symmetrical stitch shape (i.e., to equalize tensions) equals half the base width *D*. Consequently, less shift occurs with closely spaced stitches (*upper right*) than with widely spaced stitches (*lower right*)

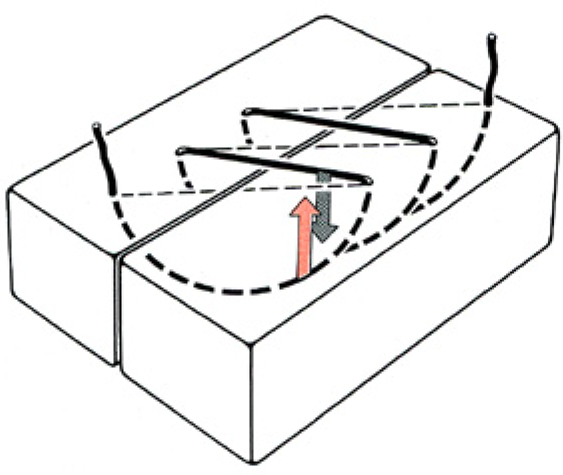


Fig. 2.113. **Effect of suture spacing on wound inversion or eversion, illustrated for the overlapping sawtooth stitch.** When the intramural and bridging segments are close together, so that they are nearly on the same plane, the tendency toward wound inversion or eversion is largely neutralized, and a smooth tissue surface is obtained

back to index

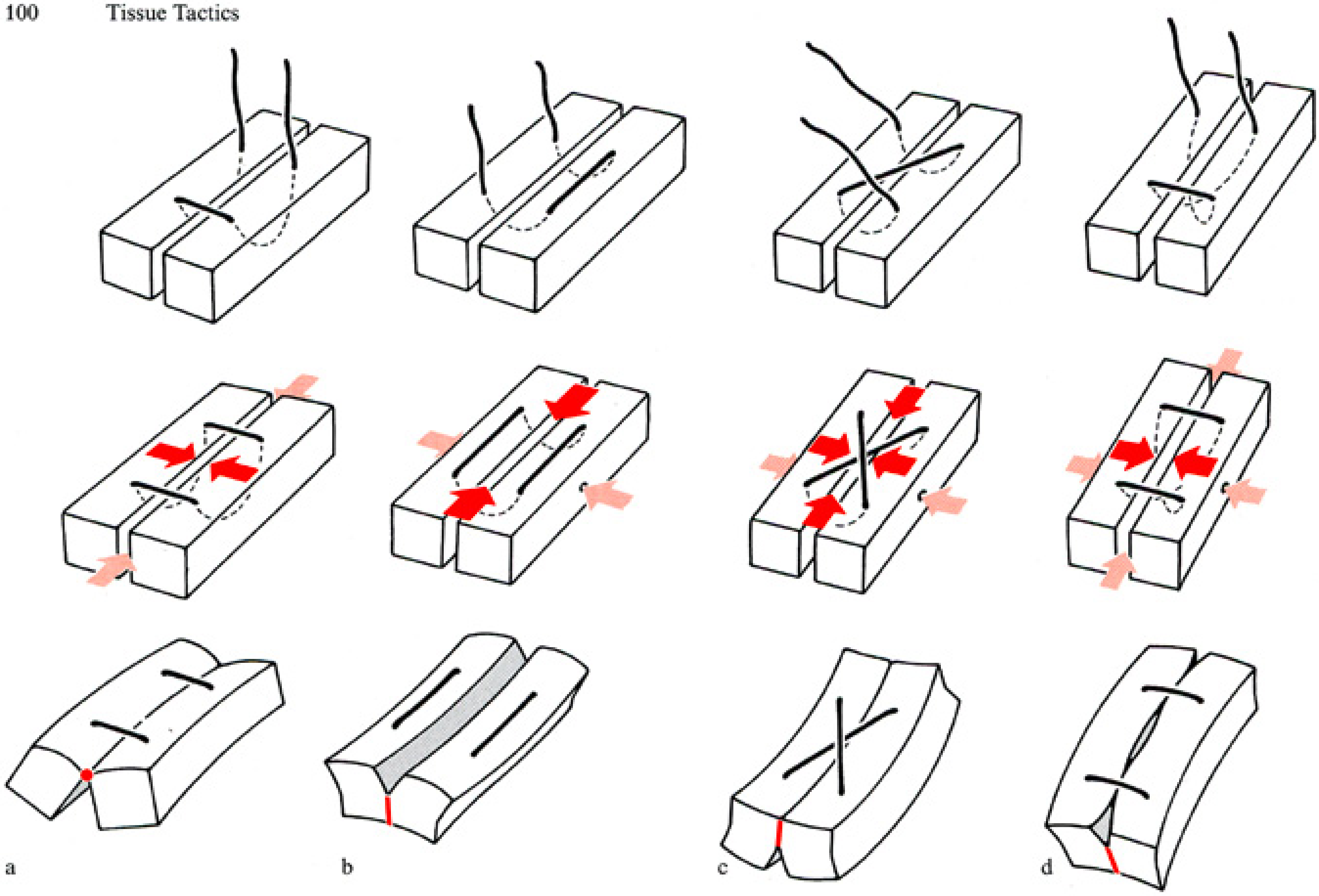


Fig. 2.114. **Mattress sutures**. The force vectors of the bridging segments are fully active (*red arrows*), while those of the intramural segments are checked by tissue resistance (*pink arrows*).

a Uncrossed inverting mattress suture: The suture bridges the wound surface but does not pierce it. No compression zones are produced. Maximum, unchecked inversion is produced transversely. A slight everting action is produced longitudinally.

b Uncrossed everting mattress suture: The intramural segments pierce the wound surface and are perpendicular to it. Significant eversion is produced transversely by deep compression of the wound surfaces.

c Crossed inverting mattress suture: The crossed portion is external, and the intramural portions are perpendicular to the wound. The bridging segment produces an inverting action both transversely and longitudinally, the transverse component being partially offset by deep everting vectors. The synergism of the deep and superficial compressing vectors effects compression which is active mainly at the superficial portions of the wound.

d Crossed everting mattress suture: The crossed portion is internal. The intramural segment is oblique to the wound surface and therefore the compression zone is broad and extends the full length of the stitch. An everting action is produced both transversely and longitudinally, the transverse component being partially offset by the inverting action of the bridging segment. The synergism of the deep and superficial compressing vector components affords good compression, which, in contrast to **c**, mainly affects the deep portions of the wound

Mattress Sutures

Mattress sutures are intermediate between simple interrupted sutures and continuous sutures in their function. On the one hand, they may produce *wider compression zones* than simple interrupted sutures; on the other, *local tension* can be controlled better than with simple continuous sutures.

Mattress sutures tend to produce inversion and eversion not just in the transverse direction[65] but also longitudinally.[66] These tendencies may be synergistic or antagonistic, i.e., may lead to a generalized inver-

[65] Caused by the vertical vectors (see Fig. 2.108).

[66] Caused by the lateral shift vectors, which tend to shorten the suture line. This effect is not checked by friction because of the short suture length, so inverting and everting components can become active.

sion or eversion of the wound margins or a combination of both.

Uncrossed mattress sutures produce *strong inversion or eversion* of the wound edges, with little (Fig. 2.114b) or no (Fig. 2.114a) *compressive effect*.

In **crossed mattress sutures** *compression* is most effective when the stitch is crossed intramurally (Fig. 2.114d). The *side-effects* are more pronounced when the stitch is crossed on the tissue surface (Fig. 2.114c).

Countersutures

Lateral shift vectors in a continuous suture line can be completely neutralized by placing a countersuture. The opposing tensions of the double suture lines also produce a general *shortening* of the wound. But this effect is not significant if the wound is long and there is sufficient friction to resist the shortening tendency.[67]

The *compression zones* are no wider than in a single suture line. However, the *force* of the compression is increased, whether by doubling the force applied from one side of the wound (Fig. 2.115c) or by creating a counterforce on the opposite side (Fig. 2.115b).

The *vertical vectors* are neutralized in some suture patterns. This occurs at sites where the intramural and bridging segments of the two suture lines overlap (Fig. 2.115a, c). In stitches where the intramural and bridging segments do not overlap, vertical vectors are increased (Fig. 2.115b).

[67] This is in contrast to the mattress suture, where the shortening effect may be significant.

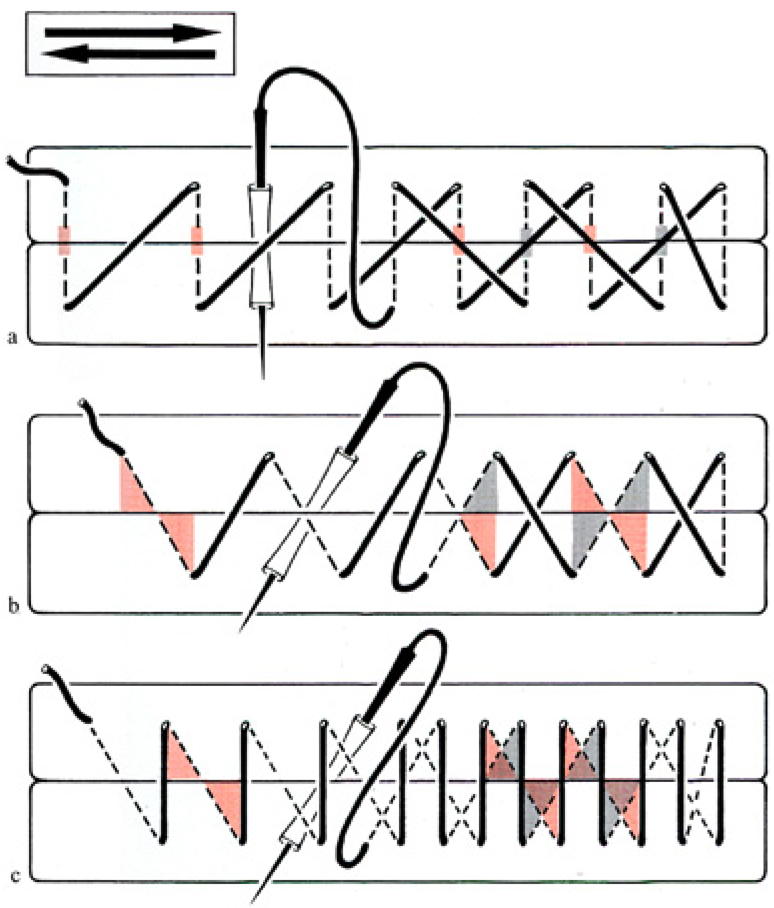


Fig. 2.115. **Analysis of countersutures**

a Double sawtooth suture: The intramural segments are perpendicular, and the compression zones are narrow, although there are twice as many of them as in the single sawtooth suture. The lateral shift vectors produced by one suture line are neutralized by the countersuture. The inverting and everting vectors also are largely neutralized because the bridging segments cross the intramural segments.

b Symmetrical double sawtooth suture: The intramural and bridging segments are oblique to the wound line. The compression zones are not wider than in a simple, symmetrical running suture (see Fig. 2.111b), but their effect is enhanced because they act on both sides of the wound. The lateral shift vectors are neutralized. The inverting and everting vectors of both suture lines are in the same segment, so their effects are additive, and the tissue surface becomes irregular.

c Inverted double sawtooth suture: The intramural segments are oblique, the bridging segments perpendicular to the wound line. The compression zones are contiguous (see Fig. 2.111c). Their force is doubled but acts on only one side of the wound at any given site. The lateral shift vectors cancel out. The inverting and everting vectors are neutralized by the superposition of the intramural and bridging segments

back to index

Lock-Stitch Sutures

The lock-stitch suture is a continuous suture in which the thread is passed through the previous loop before the needle is reinserted.

On the one hand, such sutures have the properties of *simple interrupted sutures* in that the bridging and intramural segments are on the same plane. But they are also like *simple continuous sutures* in that they distribute tension evenly, since the individual loops are fixed only by the relatively low friction of the bridging segments.

Lock-stitch sutures have two main applications. First, they can be used like *simple running sutures* in cases where it is advantageous to equalize the tension between the individual loops (Fig. 2.116a). Second, they can be used for *tacking one tissue layer onto another* (Fig. 2.116b).[68] This technique utilizes the compressive effect not of the loops but of the linking segments.

Lock-stitch structures differ from simple running sutures in that the wound edges do not shift laterally when the suture is pulled tight. The tightening causes a *shortening of the linking segments* which, as they tend toward linearity, are forced onto the shortest path connecting the two ends of the suture. This tendency can be utilized to adjust the position of the linking segments by appropriate angling of the suture (Fig. 2.117).

In a **meandering suture** the position of the linking segments is fixed. The *intramural* segments produce an *everting* effect, while the *linking* segments can be used for tacking, as in the lock-stitch suture. In their *simple form*, meandering sutures have discontinuous overlying segments. In the *reverse form* the overlying segments form a continuous zone whose position is fixed and not altered by suture tension (Fig. 2.118).

[68] Example: Tacking a conjunctival flap to the cornea or sclera (see also Figs. 4.26–4.28).

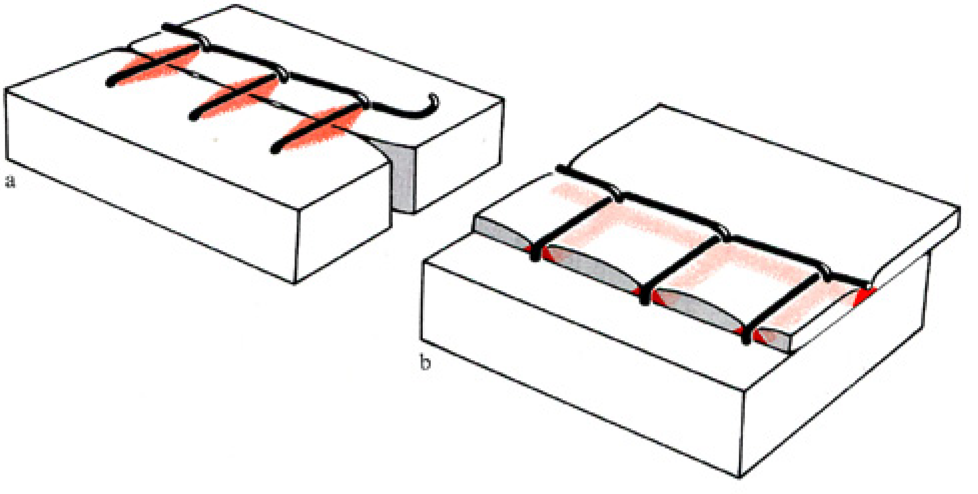


Fig. 2.116. **Applications of a lock-stitch suture**

a *Compression suture*, whose tension can be regulated by adjusting the tension of the linking segments. The compression zones are like those produced by simple interrupted sutures (see Fig. 2.109).

b *Tacking stitch*: The bridging segments are used to form a broad, continuous compression zone (*pink*) that can fix one tissue layer to another

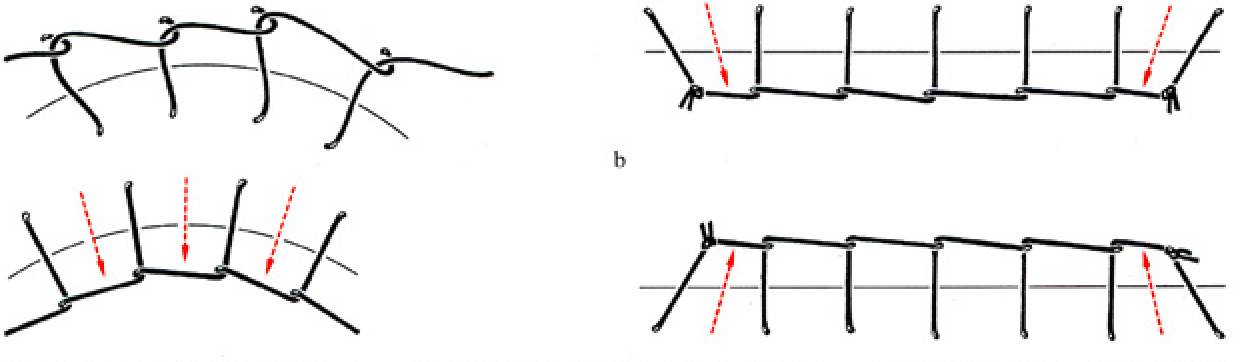


Fig. 2.117. **Behavior of a lock-stitch suture on tightening.** When the suture is tightened, the linking segments are forced onto the shortest connecting line.

a On curved wound lines (*above*), the linking segments are drawn toward the center of curvature (*below*).

b On straight wound lines, the position of the linking segments is controlled by angling the ends of the suture to shorten the upper or lower connecting line

back to index

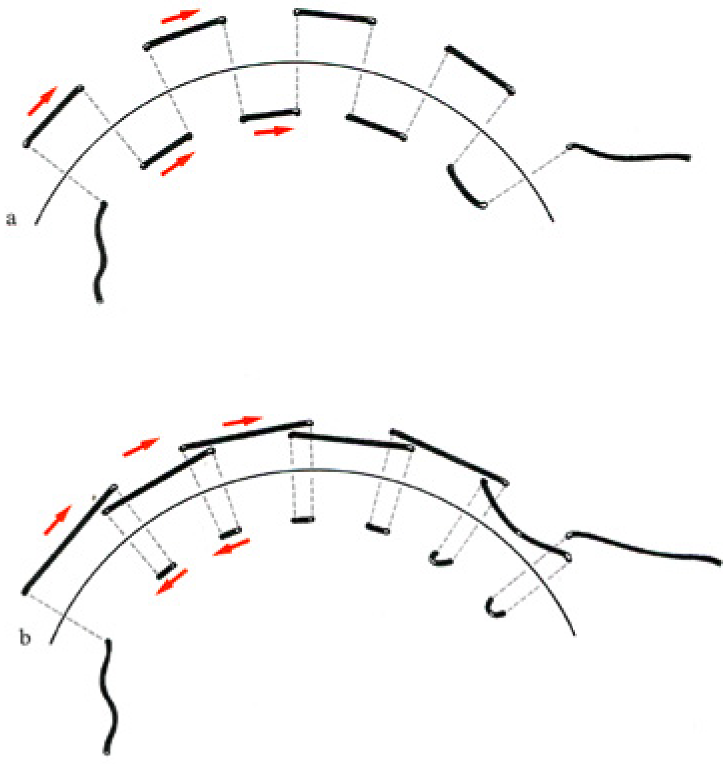


Fig. 2.118. **Meandering sutures**

a The linking segments are discontinuous in this stitch, and they do not change their position when tightened.

b The reverse meandering suture creates a continuous, overlapping series of linking segments

Relationship of the Suture and Needle Track

If the needle has a larger diameter than the suture material, the needle track also will have a larger diameter. This may allow the suture to shift inside the track, and the wound edges may shift relative to the splinting material (Fig. 2.119).

This means that when a thin thread is pulled tight inside a larger needle track, it will assume a *position* that may be *different from that which the surgeon intended* and defined by his guidance actions. The thread is forced onto the shortest connecting path, which may lie closer to the surface, wound margin, or adjacent suture depending on the cross-section of the track (Fig. 2.120). The final thread position is especially difficult to predict if the needle track is oblique, but it can be estimated beforehand by a tensile test (Fig. 2.125) and corrected to some degree by modifying the thread tension.

Shifting of the thread within the needle track allows thread shortening with no consequent tissue deformation and can even serve to correct minor deficiencies in the placement of the track (Figs. 2.121, 2.122). However, the discrepancy between the intent of the surgeon (guidance of needle tip) and the result (position of the thread axis) carries a risk of faulty apposition. When thin threads are used, therefore, their shifting tendency must be anticipated and allowed for when selecting the needle (which determines the cross-section of the track, see Fig. 2.91).

The *splinting action* of thin threads is likely to improve during the course of wound healing as the needle track gradually cicatrizes and its cross-section approaches that of the suture. A process with the *opposite effect* may also occur, however: The track may dilate due to an inflammatory response which varies in intensity with the tissue compatibility of the suture material

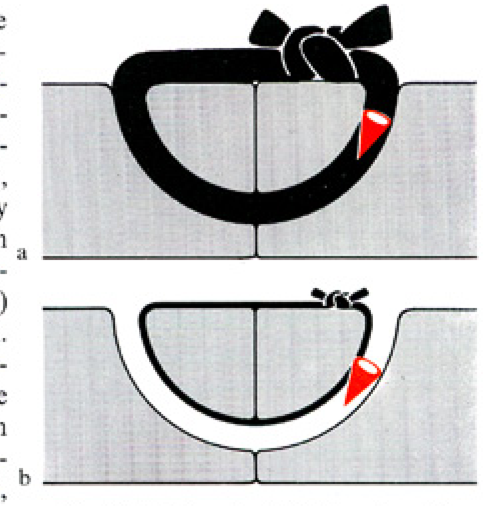


Fig. 2.119. **Disparity in the diameters of the suture and needle track**

a A suture acts as a splint if the thread size matches the lumen of the needle track. In this case the thread axis equals the path of the needle tip (*red*) and coincides with its guidance direction.

b If the thread is much thinner than the needle track, its final position is not on the path of the needle tip but on the shortest connecting path

back to index

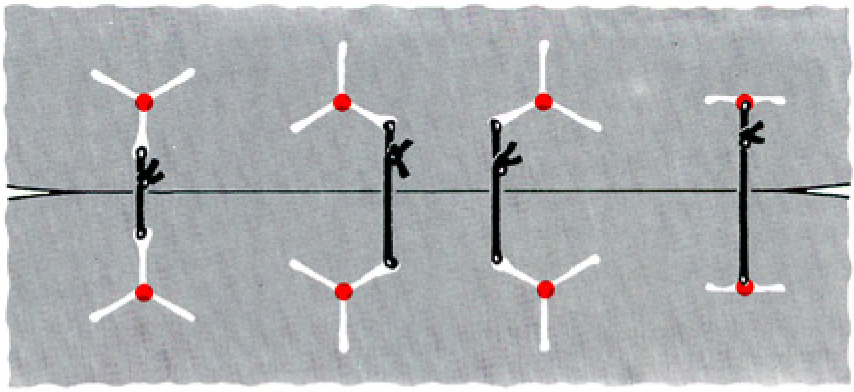


Fig. 2.120. **Shifting of thin threads in the needle track.** The shortest connecting path within the track varies with the cross section of the track. In the track cut by a triangular needle (see Fig. 2.91), the thread shifts away from the path of the needle tip (*red*), moving closer to the wound margin (*left*) or into one of the side arms (*center*). In a slitlike track (*right*) the thread remains centered only if the track is exactly perpendicular to the wound line

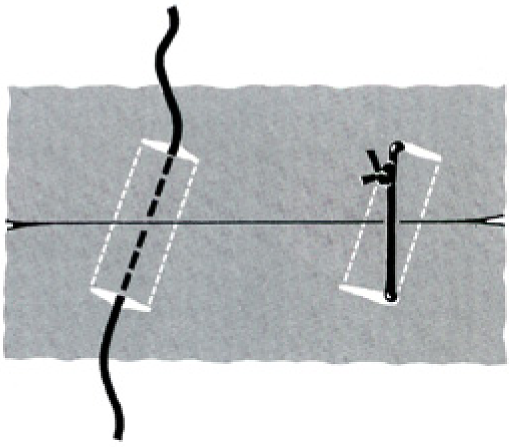


Fig. 2.121. **Shifting of thin threads in an oblique needle track.** When a thin thread is tightened in an oblique needle track, vector components parallel to the wound margin tend to force the thread onto a path perpendicular to the wound. If the needle track is wide enough, the thread may shift with no associated shifting of the wound edges ("self-correction of oblique thread placement")

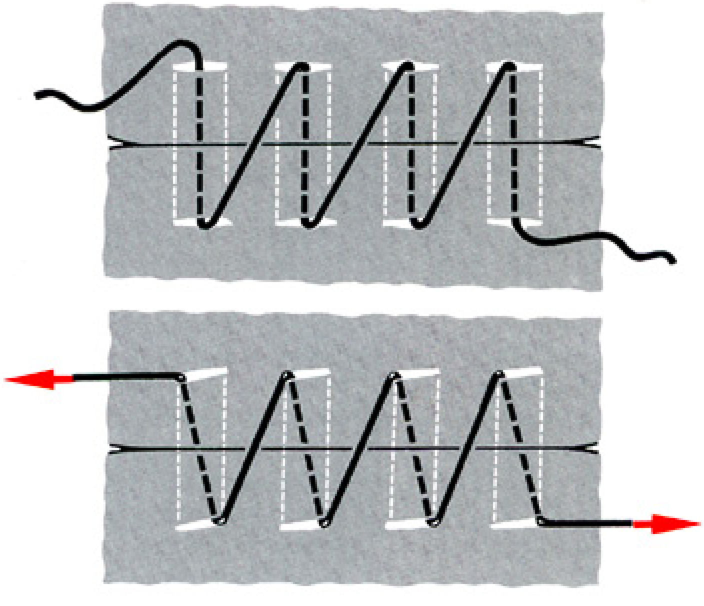


Fig. 2.122. **Shifting of thin threads in a continuous suture line.** In a simple sawtooth suture (*top*), tension can equalize spontaneously by the shifting of the thread in its track (*bottom*). This avoids any lateral shifting of the wound edges

back to index

❮ ❯

Table 2.1

	A Wire	B Twine	C Sheathed twine
Surface	smooth	rough	smooth
Flexibility	low	high	high
Distensibility	depends on material	good	depends on material and thickness of sheath
Tissue compatibility	good	fair	good

Generally it may be assumed that commercially available suture materials have good tissue compatibility. For a given material, the thinner, smoother and more flexible the thread, the better its compatibility.

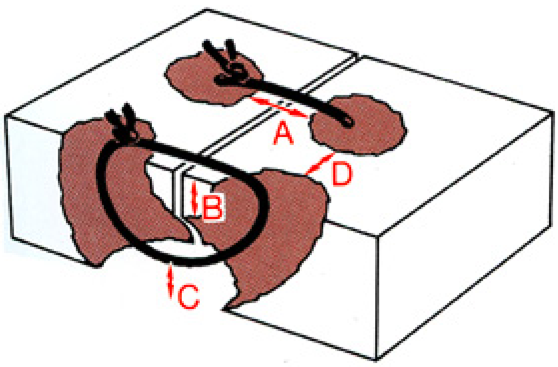


Fig. 2.123. **Effect of the inflammatory canal on suture spacing**. The development of an inflammatory canal shortens the distance from the suture tract to the wound margin (*A*), outer tissue surface (*B*), inner surface (*C*), and adjacent sutures (*D*). Hence, with sutures that incite an inflammatory response, larger values must be chosen for A, B, C, and D than with a nonirritating suture material

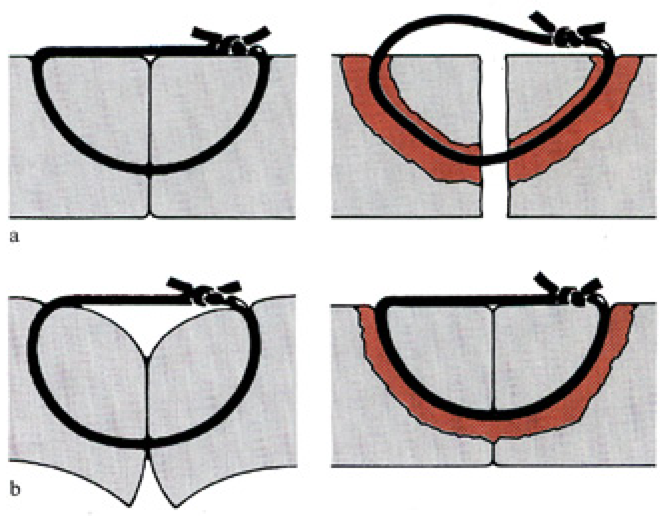


Fig. 2.124. **Effect of inflammatory canal on wound approximation**

a Threads correctly placed initially (*left*) are loosened by expansion of the suture track in the postoperative period, and wound approximation is lost (*right*).

b The wound deformation caused by overtightened threads (*left*) is spontaneously relieved by the loosening effect of the inflammatory canal (*right*): "Self-adaption of overtightened sutures"

(Table 2.1), and an "**inflammatory canal**" may develop around the thread (Fig. 2.123). This process can be favorable, however, in that it can loosen overtight threads as healing progresses and thus reverse the initial tissue deformations caused by compression sutures (Fig. 2.124).

The possible formation of an inflammatory canal should always be considered in the operative plan, for it influences the **selection of suture material**. Sutures placed close to the wound edges, tissue surface, or adjacent sutures should be made of a *nonirritating* material.[69] On the other hand, compressing sutures that produce primary tissue deformation may be made from a mildly *irritating* material so that the subsequent tissue reaction and loosening effect will correct the initial deformation.[70]

[69] Example: Monofilament polymer.
[70] Example: Twisted, braided or coated silk.

back to index

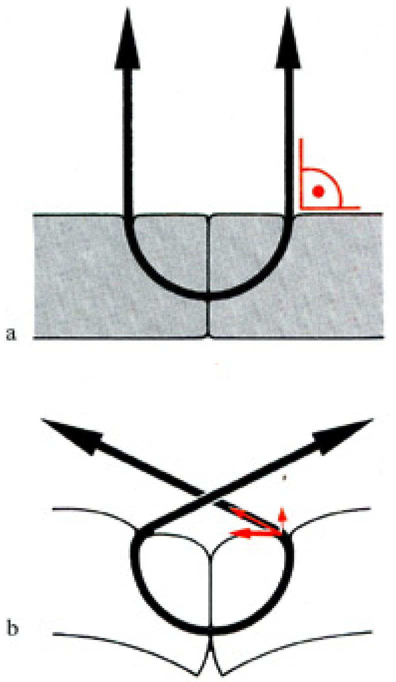


Fig. 2.125. **Effects of suture tightening**

a The distance between the entry and exit sites of the suture is not affected by pulling the ends of the thread vertically upward.

b If the suture ends are pulled together during tightening, vectors form in the direction of the wound margins, and the entry and exit sites move closer together

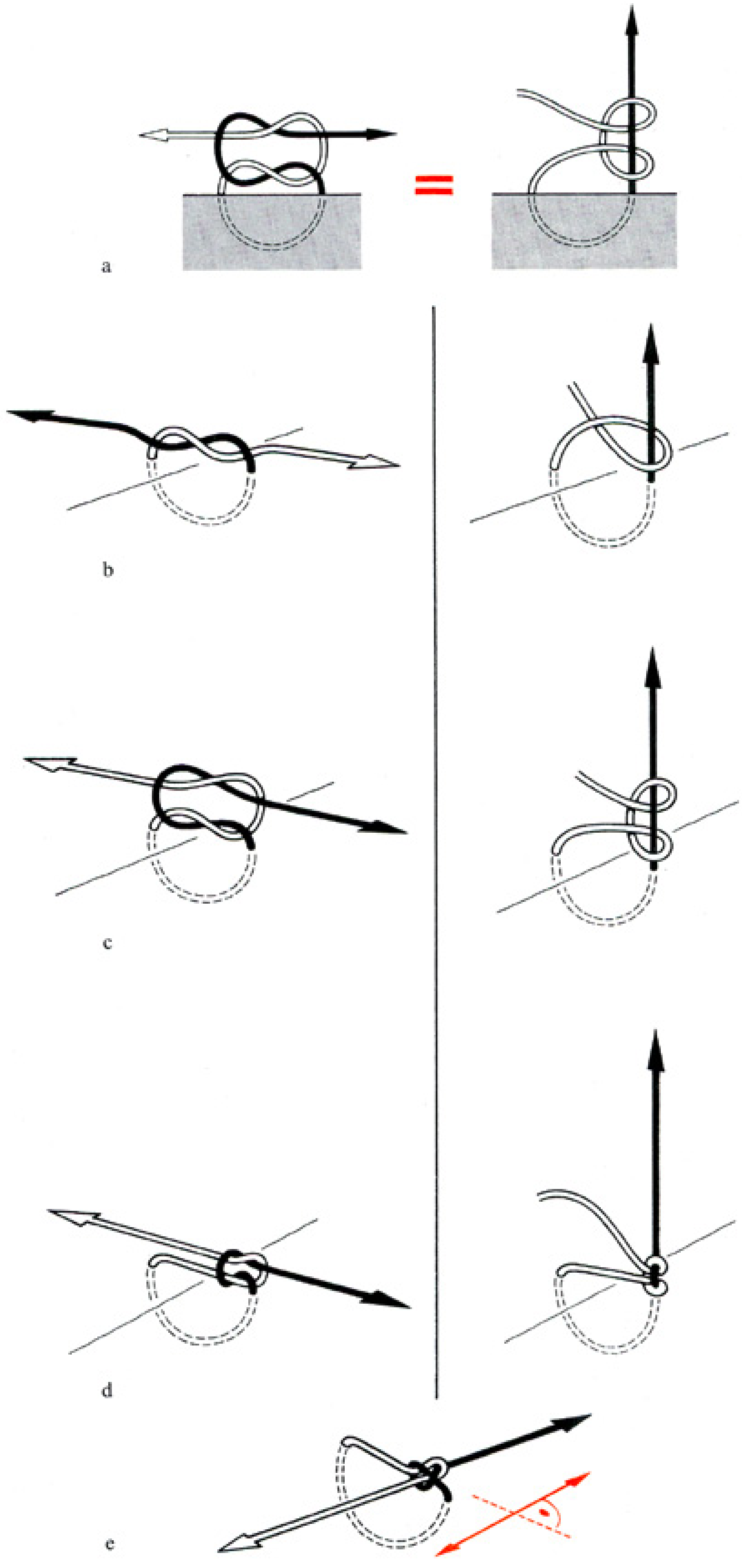


Fig. 2.126. **The square knot and slip knot** ►

a Starting with the same initial loop arrangement, a simultaneous horizontal pull on both ends of the thread makes a square knot (*left column*), while a vertical pull on only one end makes a slip knot (*right column*).

b Making the approximating loop: The square knot (*left*) is already in the correct position; the slip knot (*right*) is still loose.

c Making the securing loop.

d Positioning the knot.

e The securing loop is tightened at right angles to the suture plane so that it will not affect the established suture tension

back to index

Knots

When a suture is tied, all forces should be applied so that the position of the wound edges is not changed. The *rule of vector separation* is helpful for avoiding vector components directed toward the wound line: Tightening the thread in the needle track is done separately from the tying maneuver (Fig. 2.125), and the direction of pull on the securing loops is at right angles to that on the approximating loops (Fig. 2.126e).

The **holding strength** of knots depends largely on the *friction* that is created within the tightened loops. Hence the quality of the suture material plays an important role: its surface roughness, compressibility, and flexibility. The less friction produced by the material, the greater the contact area that must be established by the knotting technique.

The first loop, called the *approximating loop*, performs the actual suturing function: It apposes and fixes the wound edges in the desired position. All *additional loops* serve only to secure the approximating loop.

In **square knots** the approximating loop is first placed in its definitive position and held there while the securing loop is tied (Fig. 2.126 *left*). In **slip knots** the approximating and securing loops are first tied loosely and then drawn together into the correct position (Fig. 2.126 *right*). Both knots can be tied from the same initial loop arrangement, and only the direction of traction on the threads determines which type of knot will result.

The knot preferred in a given case depends largely on the *frictional characteristics* of the suture material. *Rough threads* favor square knots because their high friction holds the approximating loop in place. They make poor slip knots, because the knots may close before they are correctly positioned. In contrast, *smooth threads* are easily

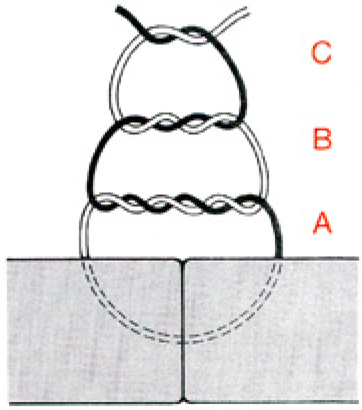


Fig. 2.127. **The reinforced knot**
A Approximating loop. *B*, *C* Securing loops.
A The friction that maintains the position of the approximating loop until the securing loops are tied can be increased by passing the thread through the loop several times (here: Three).
B If the first securing loop were much shorter than the approximating loop, it would deform it, and in elastic suture material the resulting forces could reopen the knot. To make the loop lengths more equal, the thread is also passed repeatedly (here: Twice) through the securing loop.
C With stiff suture material, a second securing loop can be placed to reinforce the first

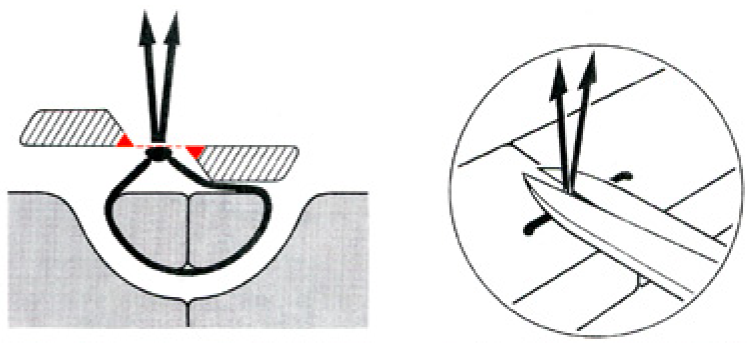


Fig. 2.128. **Cutting the ends of the thread close to the knot with a scissors.** The knot is pulled up against the cutting point, the degree of traction depending on the thickness of the blades. Since the knot is hidden behind the scissors, the best view is obtained by cutting with the tips of the blades

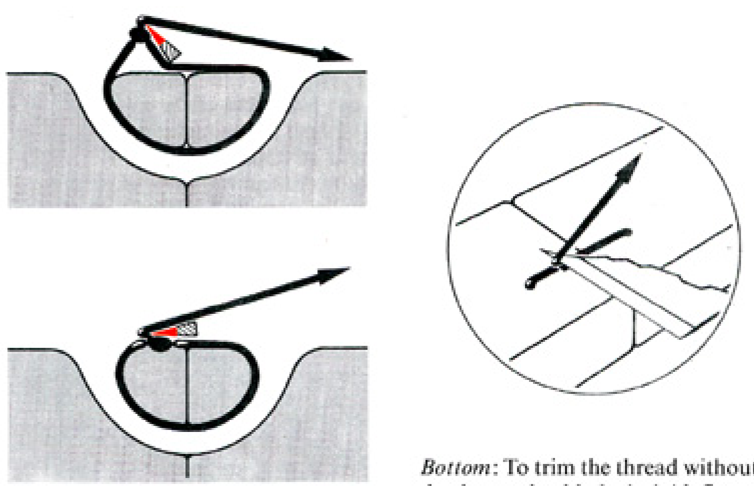


Fig. 2.129. **Cutting the ends of the thread close to the knot with a razor blade tip**
Top: If loop tension allows the thread to be pulled upward slightly, the blade can be angled to improve vision. The knot is pulled up against the cutting edge, the ends of the thread are stretched over it and, with the blade stationary, are snapped off with a quick tug.
Bottom: To trim the thread without raising the loop, the blade is laid flat over the knot, its cutting edge flush with the edge of the knot. Then the end of the thread is drawn back and snapped off with a quick tug. It is not necessary to see the knot in this maneuver, since the relation between the cutting edge and edge of the knot is precisely established before cutting and remains unchanged when the thread is cut

back to index

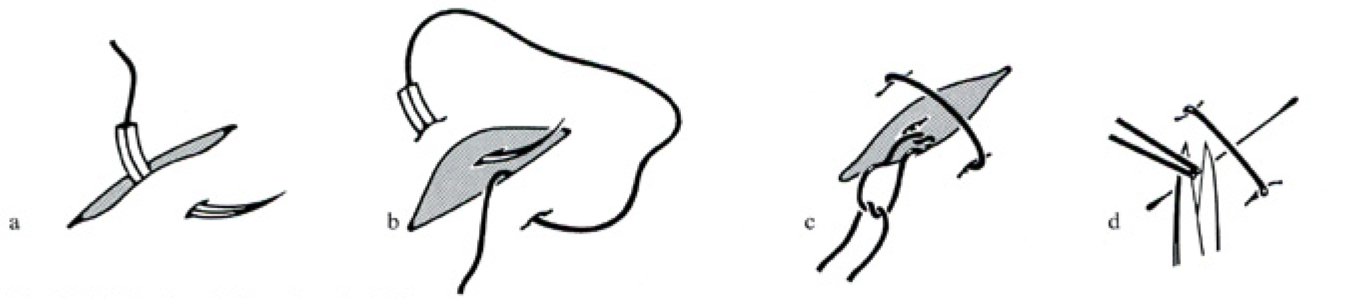


Fig. 2.130. **Burying the knot in a simple interrupted suture**

a, b The needle is inserted through the wound surface from the inside, brought out, then reinserted into the second wound surface from the opposite side. It can be difficult to pierce the second wound surface at a site exactly opposite the insertion site, but in case of thin suture material in a larger needle track any lack of precision in wound approximation may be remedied by "self adaption" (see Fig. 2.121).

c The knot is tied between the wound surfaces.

d The thread ends are cut flush with the tissue surface

tied into slip knots but are not good for square knots because the approximating loop tends to loosen before the securing loop is tied. The friction can be increased by passing the thread repeatedly through the loops, but of course this results in a bulkier knot (Fig. 2.127).

Knots left on *tissue surfaces* are a source of irritation, but this can be minimized by clipping the threads as close to the knot as possible (Figs. 2.128 and 2.129).

If the suture material is sufficiently tissue-compatible, the knot may be buried within the tissue. Either the stitch is begun from inside the wound (Figs. 2.130 and 2.131) or, if the threads are so fine that the knot is much smaller than the lumen of the needle track, the knot may be pulled into the track after it is tied (Fig. 2.132).

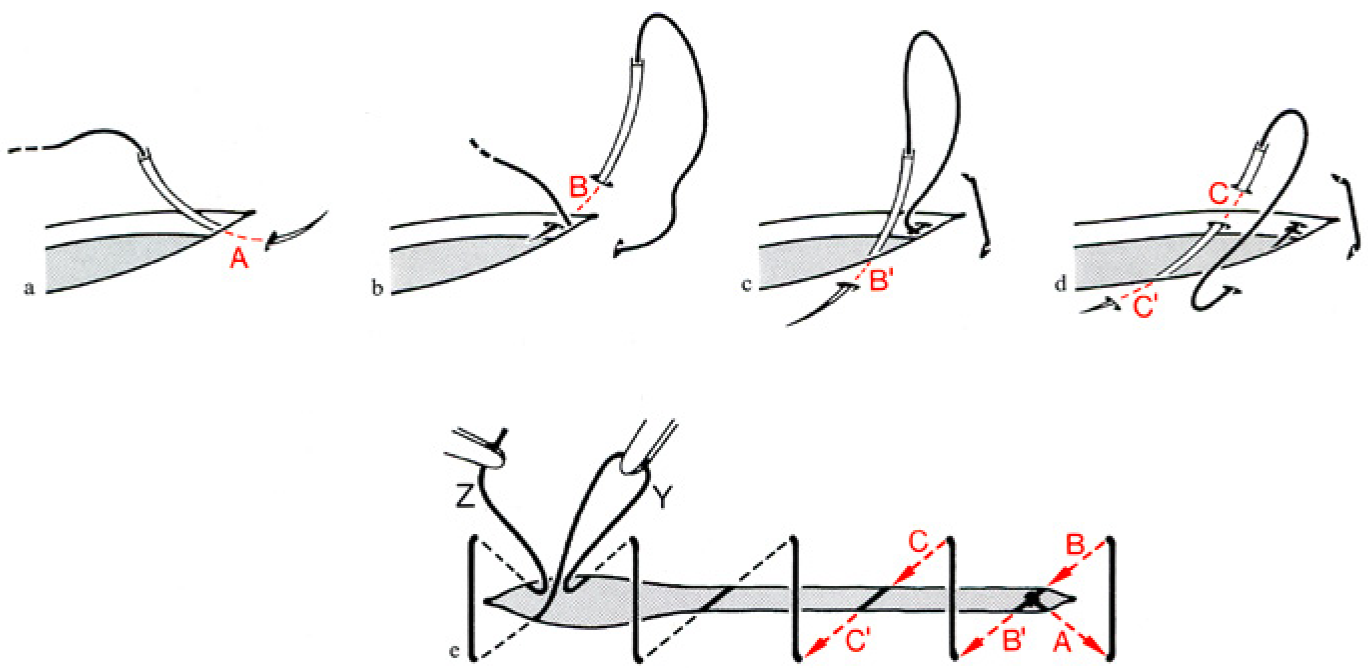


Fig. 2.131. **Burying the knot in a continuous suture**

a The needle is inserted from inside the wound and brought out at a point (*A*) past the end of the incision (see Fig. 2.110a).

b The needle is reinserted at a corresponding point on the other side of the incision (*B*), piercing the opposing wound surface at a point opposite the original insertion site.

c The suture is tied, and the needle is reinserted through the wound surface and brought out at *B'*.

d Continuation of the running suture.

e The final stitch is made past the end of the incision, as in **a**. The final knot is tied between a loop brought out from the wound surfaces at *Y*, and the end of the thread (*Z*)

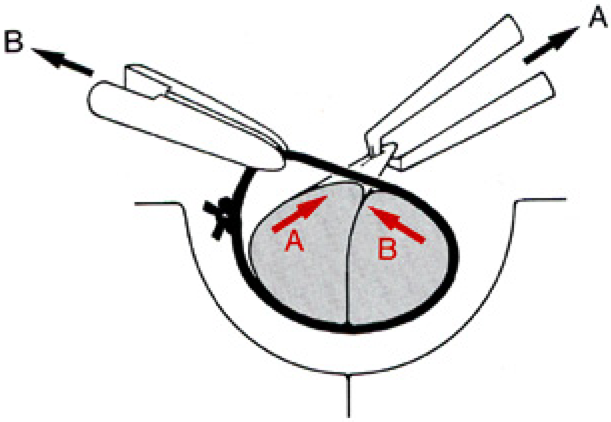


Fig. 2.132. **Advancing the knot into the suture tract**. The tissue encircled by the loop is compressed briefly so that the knot can slip over the step at the entrance to the track. This is done by pulling on the thread (*B*) while applying countertraction with a forceps (*A*)

2.2 Application of Heat

The application of heat to tissue raises the temperature of the tissue and alters it by *coagulation*, *shrinkage*, or *carbonization*. An effect that is desired at one site may be deleterious at another.[71] Accordingly, the control of heat application consists in achieving a precisely defined *temperature* within a precisely defined *tissue volume* at a specified *location*.

The desired temperature is achieved by delivering a specific quantity of heat to the target site. This heat may be produced outside the tissue and then *transferred* to it via a conductor, or it may be *generated* within the tissue itself (Fig. 2.133).

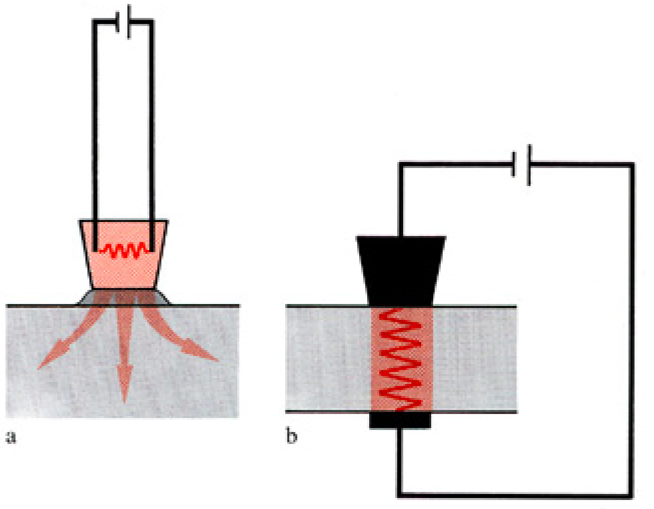
The preferred **technique of application** depends on the size of the tissue volume to be heated and on whether a superficial or deep effect is desired. Techniques suitable for some tasks may be inappropriate for others, producing a greater- or less-than-optimum effect. For example, a technique suitable for heating a large tissue volume would produce over-effect in a smaller volume.

Two physical processes that complicate the precise **control** of tissue heating are *conduction* and *convection*.[72] Since both parameters change during heat application, control based on digital readouts (temperature of a cautery or cryode, voltage of a diathermy current) is not reliable. The only way to monitor heat application is by noting the visible effects on the tissue and regulating the heat input accordingly. Thus, control is effective only in cases where the tissue changes can be observed directly or by ophthalmoscopy.

Fig. 2.133. **Methods of heating tissue**

a Transmitting heat to the tissue: Heat produced outside the tissue is transferred to the target site. The critical factors are thermal conductivity and heat capacity.

b Generating heat in the tissue (diathermy): The heat is generated at the target site. The critical factors are the electrical properties of the tissue



[71] For example, hemostasis (shrinkage of vessel walls and coagulation of their contents) should not affect surrounding tissues to the extent that wound edges are deformed and reapproximation is impaired. Hence, deep effects must be avoided, and intraocular structures must be spared. On the other hand, deep effects are desired when aseptic inflammatory lesions are induced as a stimulus for scar formation (retinal detachment surgery, obliteration of the ciliary body in glaucoma surgery). In these cases excessive shrinkage of the sclera should be avoided because it could unduly raise the intraocular pressure. However, scleral contraction is necessary to produce wound dehiscence in fistulating glaucoma operations. Carbonizing temperatures are used only for the actual division of tissue.

[72] The coefficient of heat *conduction* is a material constant which, in tissues, depends basically on moisture content; it is reduced by drying. *Convection* refers to heat transfer by fluids in motion. In homogeneous tissues it depends mainly on blood flow; thus it is decreased by compression or coagulation of the vessels. Convection at surfaces is effected by free-moving fluid layers.

back to index

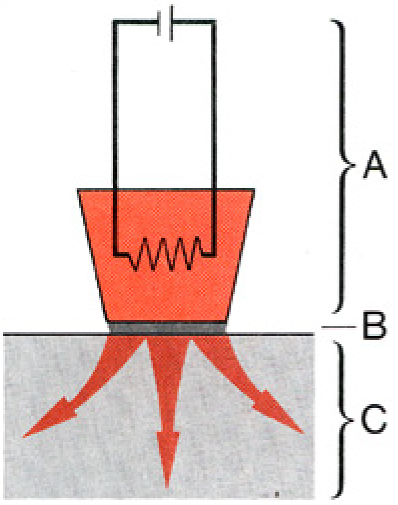


Fig. 2.134. **The heat transfer chain.** *A* Heat source. *B* Transfer resistance (tissue surface). *C* Dissipation and elimination (tissue)

2.2.1 Heat from an External Source

Heat is carried into and out of tissue in a "heat transfer chain" (Fig. 2.134) consisting of *heat production* (temperature and heat capacity of the source), *transfer* (transfer time and resistance to transfer), and *elimination* (convection).

Heat Production. Energy is invariably lost during transfer, so a *heat surplus* must be delivered by the source. This is done either by supplying an excessive quantity of heat at a precisely regulated temperature (large-capacity cautery, Fig. 2.135) or a small quantity of heat at a higher temperature (small-capacity cautery, Fig. 2.136).

Application of the precise temperature protects the tissue from overheating, but there may be insufficient space for an applicator of *large capacity*. *Small-capacity* applicators eliminate this problem but pose a danger of over-effect due to excessive temperatures.

2.135

2.136

Fig. 2.135. **Large-capacity heat source (spherical cautery).** Large dimensions = large capacity. This instrument requires a relatively long reheating time in air after it has transferred its heat to the tissue

Fig. 2.136. **Small-capacity heat source (wire loop).** Small dimensions = small capacity. This instrument transfers all its heat to the tissue upon contact, so control is difficult. Since a small capacity implies high temperatures, there is a danger of overheating at the tissue surface

Heat Transfer. Heat application is controlled most effectively by varying the transfer parameters of time and resistance. Limiting the **application time** avoids tissue overheating when excessive temperatures are used. Dabbing the target site briefly and repeatedly with the applicator allows the heat to be applied in a "digital" rather than analog fashion.

The **transfer resistance** of the tissue is a function of its moisture content. If the tissue surface is *dry* (Fig. 2.137a), the heat cannot penetrate to deep levels, and its effects will be superficial (which further increases the transfer resistance and the risk of over-effect). *Moist* surfaces allow for better heat conduction and are necessary for deep penetration (Fig. 2.137b). However, a *continuous liquid film* dissipates heat and lessens its effect on the tissue (Fig. 2.137c).

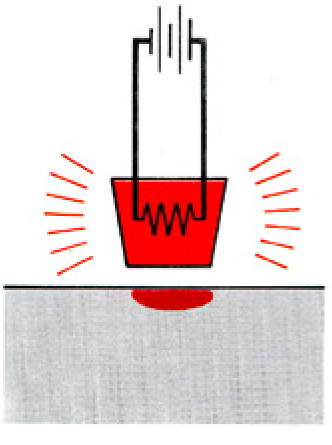
Fig. 2.137. **Methods of controlling transfer resistance**

a Heating the cautery in air. The transfer resistance is very high, and the cautery becomes very hot through retention of heat. Heating of the surrounding air dries the tissue surface, increasing its resistance to heat transfer. If the cautery is then applied to the tissue the effect is continued to its surface (danger of over-effect).

b Moistening the surface improves heat transfer to the tissue and thus enhances the deep effect.

c A thick fluid layer dissipates the heat and diminishes its effect on the tissue

2.137 a



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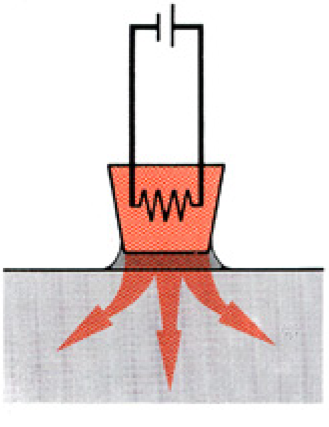

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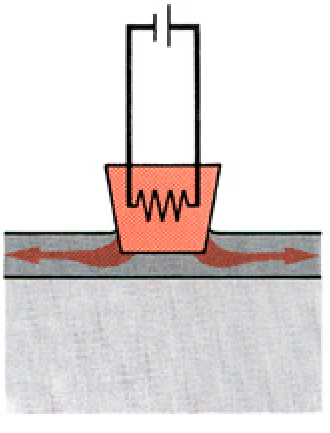


Heat Elimination. Because most heat is removed from tissue by *fluid motion*, heat elimination can be controlled by varying the *blood flow* through the affected area. The surgeon can lessen the rate of heat elimination by exerting pressure on the applicator. This produces vascular compression either directly or indirectly by raising the intraocular pressure (Fig. 2.138).

Technique of Application. The application technique involves adapting the supplied quantities of heat to the volume of tissue that is to be heated. The volume is small in very *circumscribed surface coagulation* (Fig. 2.139a), larger in the heating of *larger surfaces* by dynamic coagulation (Fig. 2.139b), and largest in *deep coagulation*, where a continuous heat influx is maintained (Fig. 2.139c). Thus, the different application techniques are appropriate for different heating requirements. A combination of different techniques is difficult to control unless the heat input (cautery temperature) is separately adjusted for each.

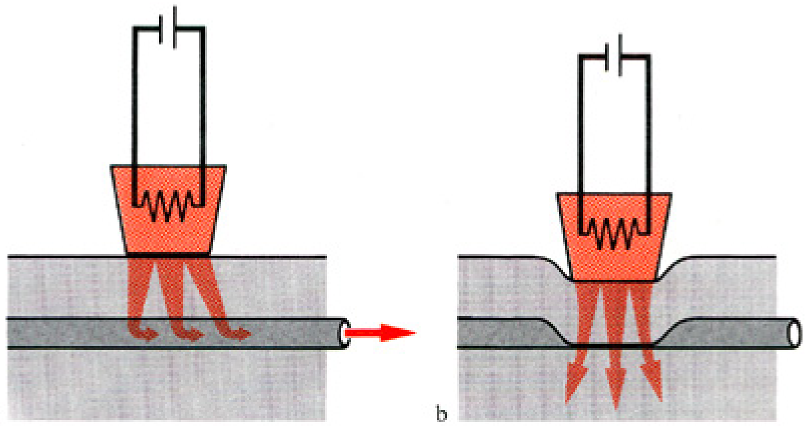
a b

2.138

Fig. 2.138. **Control of heat elimination**
a Heat is eliminated from the tissue via the bloodstream.
b Compression of the vessels interrupts the blood flow and increases the thermal effect by reducing heat loss

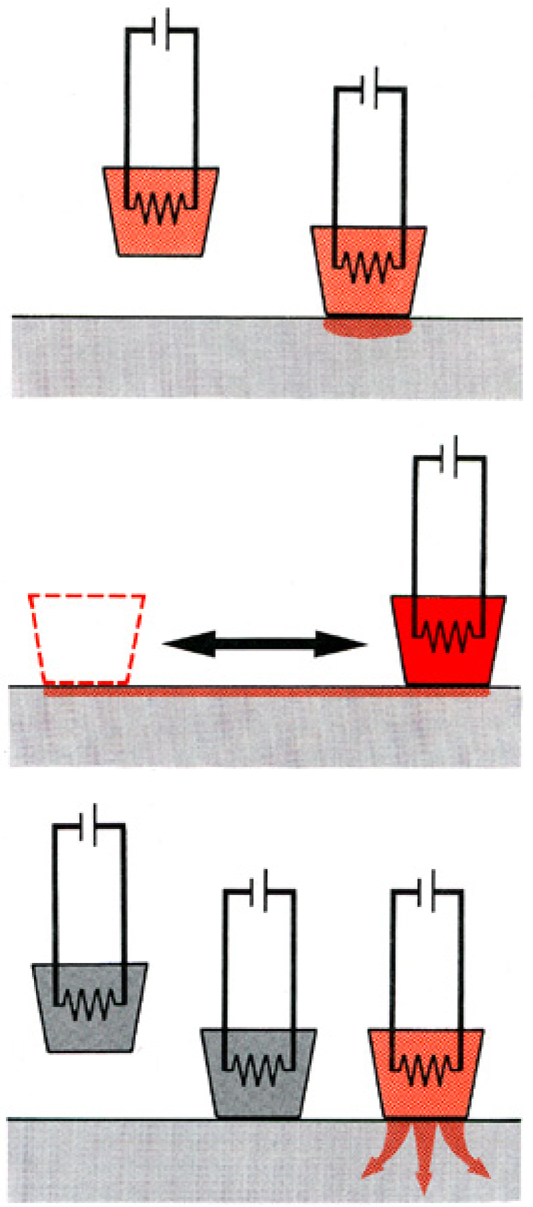
a b c

2.139

Fig. 2.139. **Modes of application of heat transmitters**
a *Surface coagulation* (*static*): The applicator is preheated and applied warm to the tissue. All heat is transferred in a circumscribed area; transfer is controlled by regulating the temperature.
b *Surface coagulation* (*dynamic*): The preheated applicator is moved back and forth on the tissue surface. Larger quantities of heat (= higher temperatures) are required than in the static method, and transfer is controlled by the speed of applicator movement.
c *Deep coagulation*: The applicator is placed onto the tissue before it is heated. Heat flows into the tissue during warmup, and some time is required for the onset of effect. Large quantities of heat are needed. The effect is difficult to assess

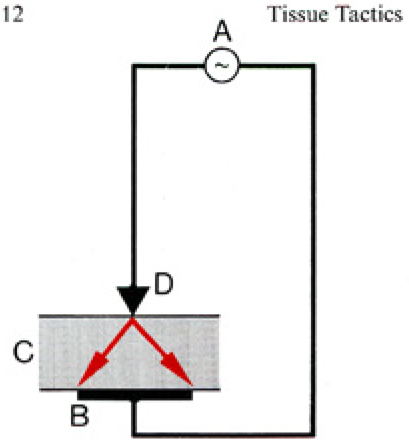


Fig. 2.140. **Electric circuit for generating heat in tissue.** *A* Voltage source. *B* Indifferent electrode. *C* Tissue resistance. *D* Active electrode

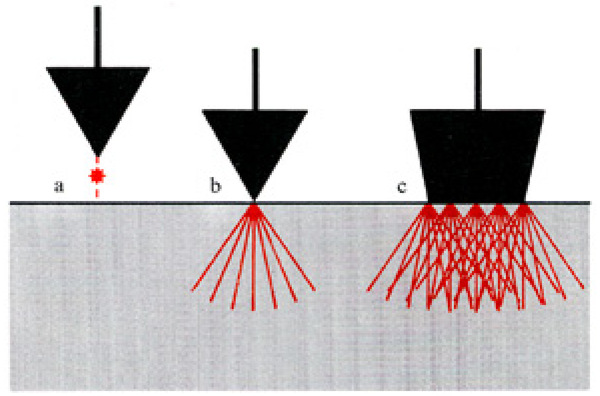


Fig. 2.141. **Contact between the active electrode and the tissue**

a If a high voltage is applied prior to tissue contact, a spark will form (with danger of tissue destruction).

b Pointed electrodes concentrate their energy at the site of application (surface).

c Flat-faced electrodes also produce a high current density at deeper levels

2.2.2 Heat Generation in Tissues

Diathermy

Heat is generated in tissues by an electric circuit consisting of the *voltage source*, the *indifferent electrode*, the *electrical resistance* of the tissue, and the *active electrode*. The **voltage source** delivers alternating current in a frequency range appropriate for the generation of heat. The **indifferent electrode** should be as large as possible to minimize the current density at that location (Fig. 2.140).

The **electrical resistance** for a given diameter and spacing of the electrodes is determined by the *electrolyte content* of the tissue. Hence it can vary during coagulation.

The **shape of the active electrode** determines the extent of tissue contact and thus the distribution of current density in the tissue (Fig. 2.141). As the *contact area* increases, the current density rises at deeper levels, but higher voltages are also required. If the same electrode is applied "at a point" in one instance and over a larger area in another (Fig. 2.142), the voltage must be adjusted accordingly.

The technique of application depends on whether the effect should be superficial or extend to deeper levels. Superficial heating is achieved by using a pointed electrode on a dry surface. Deeper heating is promoted by a moist tissue surface and a broad electrode. Of course, the limits of heat production cannot be precisely defined, and variations in the electrical properties of tissues can always lead to undesired deep effects that are not appreciated by observing the tissue surface.

Miniaturized diathermy probes: Applicators with a highly localized diathermy effect are required for intraocular use. The unipolar miniprobe (Fig. 2.143) functions without an indifferent electrode. Increasing the frequency to the megahertz range produces a tremendous

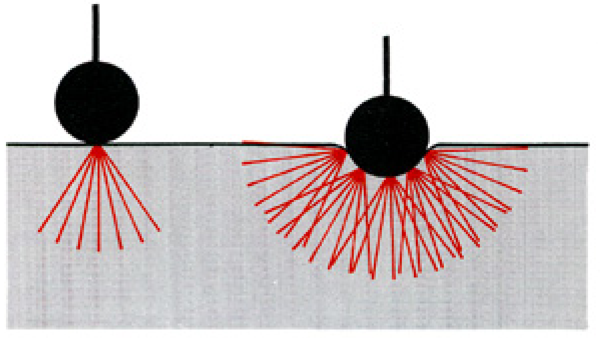


Fig. 2.142. **Spherical electrodes.** A sphere can have the same effect as a pointed or flat-faced electrode, depending on the pressure of application. The voltage must be adjusted accordingly

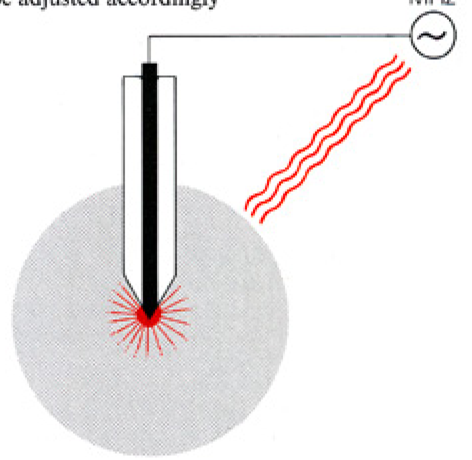


Fig. 2.143. **Unipolar miniprobe.** The heating effect is extremely concentrated owing to the high voltage and sharply pointed tip of the active electrode. A separate indifferent electrode is not required. The alternating current is returned in the form of radio waves from the patient's body (which acts as an antenna) to the current source

back to index

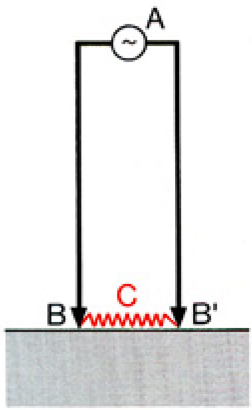


Fig. 2.144. **Electric circuit for bipolar diathermy.** *A* Voltage source. *B* and *B'* Active electrodes. *C* Heat-generating resistance

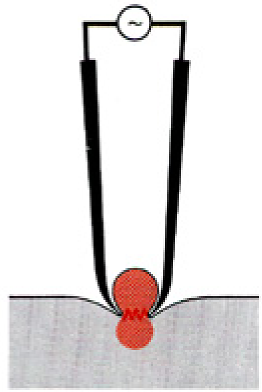


Fig. 2.145. **Direct bipolar diathermy of tissue.** The tissue grasped between the forceps blades is heated

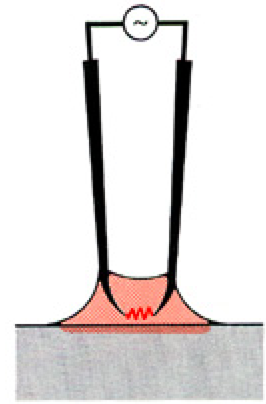


Fig. 2.146. **Indirect bipolar diathermy through a liquid film.** An electrolyte-containing liquid is heated and forms a heat-transfer medium

concentration of energy at the pointed tip of the active electrode. The energy falls off rapidly with distance from the tip, allowing for highly selective intraocular coagulation. However, remote effects may still occur as a result of impedance variations: Tissues with a low water content have a higher impedance than water-rich tissues. Other side-effects can result from stray currents induced by the presence of air bubbles in the eye or the introduction of other instruments (vitrectomy probe, fiberoptic light, etc.) into the eye.

Bipolar Diathermy

Bipolar diathermy can be used to *generate heat* in tissues as well as to *transmit heat*.

The voltage in bipolar diathermy is produced between *two* slender, identically shaped *active electrodes* (Fig. 2.144), which either grasp the tissue to be coagulated (Fig. 2.145) or are immersed in a liquid film on the tissue surface (Figs. 2.146, 2.149).[73]

When the electrodes are applied **directly to the tissue**, they act as a *diathermy*. Control is difficult, because as soon as an effect is achieved, the critical parameters are altered as a result of tissue contraction, approximation of the forceps blades, and increased resistance due to drying. Continued application will produce over-effects, so the margin between effect and over-effect is very slim.

By contrast, a very large safety margin is provided by **indirect application** where the electrodes are immersed in an electrolyte-containing film (e.g., physiologic saline) (Figs. 2.146, 2.149). The liquid film provides an *ideal heat-transfer medium* whose temperature is limited by its boiling point and whose transfer resistance remains low and constant.

The energy release is *controlled* either by changing the voltage (Fig. 2.147) or changing the electrode spacing (Fig. 2.148). When bipolar diathermy is applied in the direct mode, the energy should be released in short bursts because of the small safety margin. Indirect application requires a more prolonged energy release due to the greater length of the heat-transfer chain (which includes the liquid film). An additional means of control is the use of irrigation to dissipate heat (Fig. 2.150).

[73] Caution: Touching the forceps tips together while the voltage is on will cause a short-circuit, and the tips will fuse.

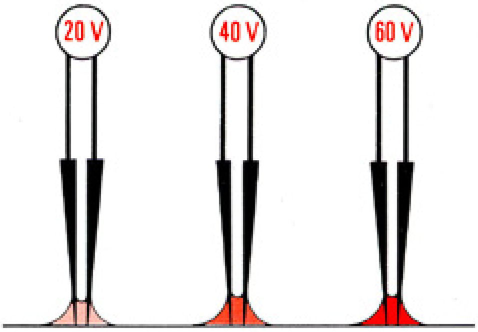


Fig. 2.147. **Control of diathermy by changing the voltage.** The electrode spacing is kept constant

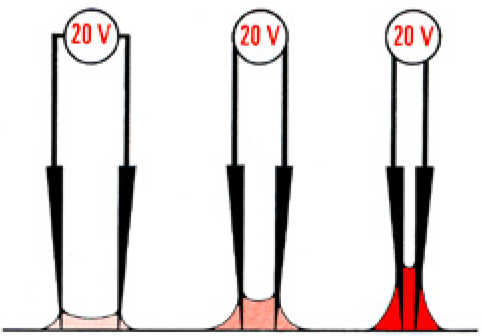


Fig. 2.148. **Control of diathermy by changing the electrode spacing.** The voltage remains constant

back to index

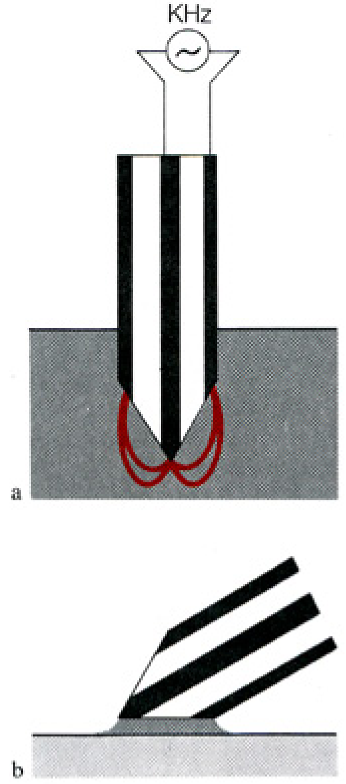
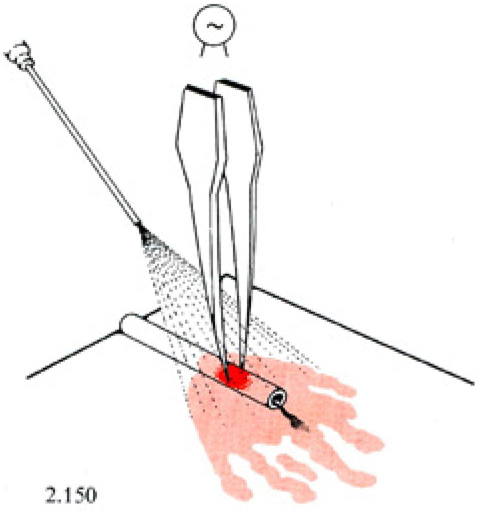


Fig. 2.149. **Bipolar miniprobe**

a The bipolar probe consists of a thin, pointed active electrode sheathed by an indifferent electrode and separated from it by an insulating layer. A current flows only when both electrodes are immersed in fluid. The heat produced is transferred to the environment.

b Surface coagulation: The probe is held obliquely in a thin fluid film so that both the tip and part of the sheath electrode are immersed in the conductive fluid layer



2.150

Fig. 2.150. **Indirect application of bipolar diathermy**, illustrated for the coagulation of a bleeding vessel. Heat dissipation is controlled by irrigating the surface during the coagulation. This prevents the large quantity of heat from spreading to deeper levels

2.2.3 Application of Cold

Cryofixation uses the cryoprobe as a mechanical *grasping instrument* by forming an ice ball that is continuous with tissue structures. The instrument exerts no pressure on the tissue and therefore causes no deformation on grasping. It can even grasp tissues whose cohesion is poor when the ice ball, whose cohesion is strong, extends to deeper levels. The disadvantage of cryofixation is that the ice mass can inadvertently encompass neighboring structures.

Deep freezing produces controlled *tissue damage* (localized aseptic inflammation) without the side-effects that are associated with the application of heat (coagulation necrosis and connective tissue shrinkage).

The **cold source** is a cryoprobe (Fig. 2.151), which induces freezing by evaporative cooling (change from a solid or liquid to a gas) or by the rapid expansion of gases (Joule-Thomson effect). Different cryoprobes differ mainly in their means of control, temperature, and associated technical costs. In *superficial freezing*, where the effect is produced by cooling the tissue below a threshold temperature (onset of freezing), further lowering of the probe temperature affects only the rate of the process. In *deep coagulation*, on the other hand, the tissue effect correlates with temperature, so it is necessary to determine the temperature on the basis of relevant biologic data.

The **resistance to cold transfer** basically depends on the same factors that govern heat transfer

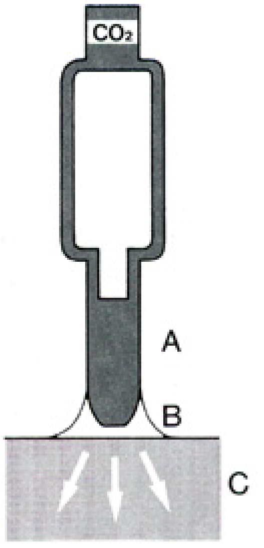


Fig. 2.151. **The cold transfer chain.** *A* Cold source (cryoprobe). *B* Transfer resistance. *C* Dissipation and elimination in the tissue

(Fig. 2.152). But the resistance may be increased by the ice mass itself, which acts as an *insulator* to retard further cold transfer from the probe to the tissue.

Ice formation in tissues depends on their *moisture content* (conduction and convection) and *electrolyte content* (freezing point). Freezing is tissue-specific, therefore, and may proceed at different rates in adjacent tissues. Thus, ice formation observed in a particular tissue layer does not necessarily signify analogous freezing of other parts.[74] These differences in freezing tendency can be utilized tactically as a means of grasping solid bodies in a liquid medium.[75]

[74] Examples: Ice formation in the relatively dry lens capsule does not necessarily mean that ice has formed in the interior of a water-rich lens (intumescent cataract, hypermature cataract). Also, the size of the ice spot on the surface of the sclera does not indicate the extent of freezing of the uvea or retina (due to interference by vascular heat conduction in the choroid).

[75] Example: Dislocated lens in the fluid vitreous.

back to index

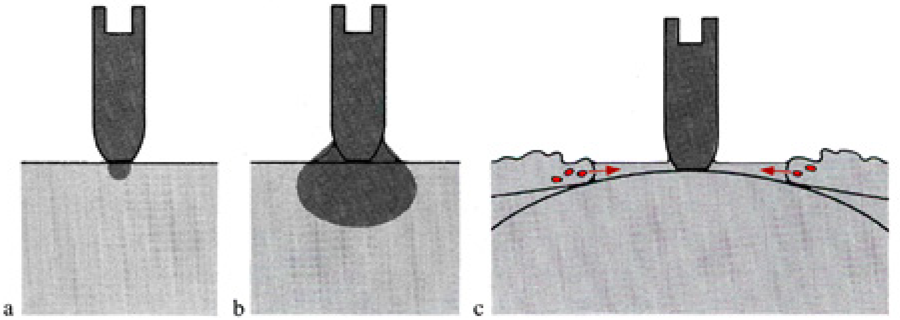


Fig. 2.152. **Control of transfer resistance**

a A dry surface has a high resistance, and very little ice forms in the tissue.

b Moist surfaces lower the transfer resistance. A large ice ball forms attaching the cryoprobe to the tissue.

c A liquid film conveys heat from surrounding structures, retarding ice formation

In the **practical application of cold** (Fig. 2.153), the *deepest penetration* is achieved when the probe is brought in contact with the tissue before it is activated. If the probe is cooled in the air before it is applied, it will acquire a frost coating that insulates against cold transfer, restricts the effect to the tissue surface, and thus provides poor adhesion for grasping.

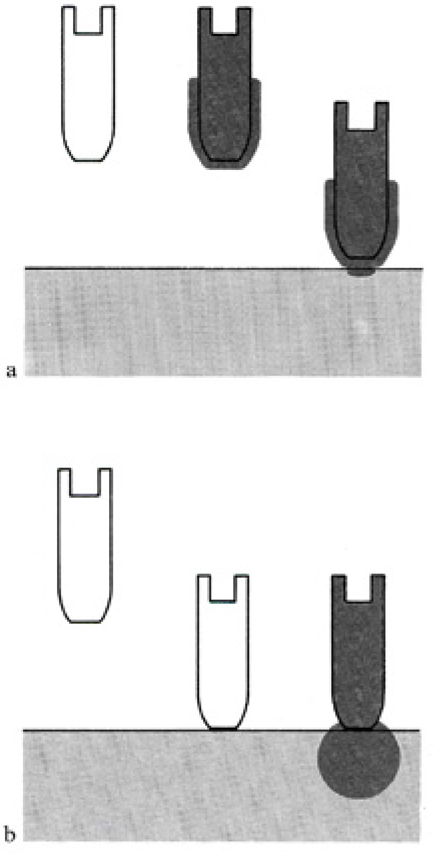


Fig. 2.153. **The application of cold**

a A cryoprobe cooled in air acquires an insulating ice film that hinders cold transmission to the tissue.

b Activating the cryoprobe only after it is applied causes a progressive temperature drop in the tissue. The penetration depth is greater, but more time is required for formation of the ice ball

2.3 Application of Light

The transport chain for heat production by concentrated photon energy consists of a *light source*, *light path*, and *heat transfer* within the tissue.

The properties of the light path determine the effect of the light. Interaction between the photons and substrate should be *minimal* on the *transmission path* leading up to the target but *maximal* at the intended site of action.

The **energy density** (power density) is controlled by focusing. Precision is highest when the energy density falls off sharply in the zones directly adjacent to the target (Fig. 2.154). This is accomplished by using an optical system that projects a highly *convergent beam* (Fig. 2.155).

The *eye* itself forms a major portion of the light path. Optical imperfections in the transparent ocular media (whose effects are additive with increasing depth) limit the accuracy of beam focusing. For best results, then, the *delivery optics* (e.g., contact lenses) must be precisely calculated for the specific site in the eye to which the energy is to be delivered.

For a given beam, increasing the *size of the light spot* at the target reduces its energy density since the total energy must remain constant. Thus, to maintain a predetermined energy density, a larger spot size requires a corresponding increase in the energy input.[76]

Absorption and transmission of the beam in a given substrate are a function of *wavelength*. Each tissue displays a *spectral selectivity*

[76] In purely geometric terms, the energy input should increase with the square of the spot diameter. But as far as the resulting effects are concerned this is only a rough guideline since increasing the spot size alters its ratio of area to circumference, and this affects heat dissipation.

back to index

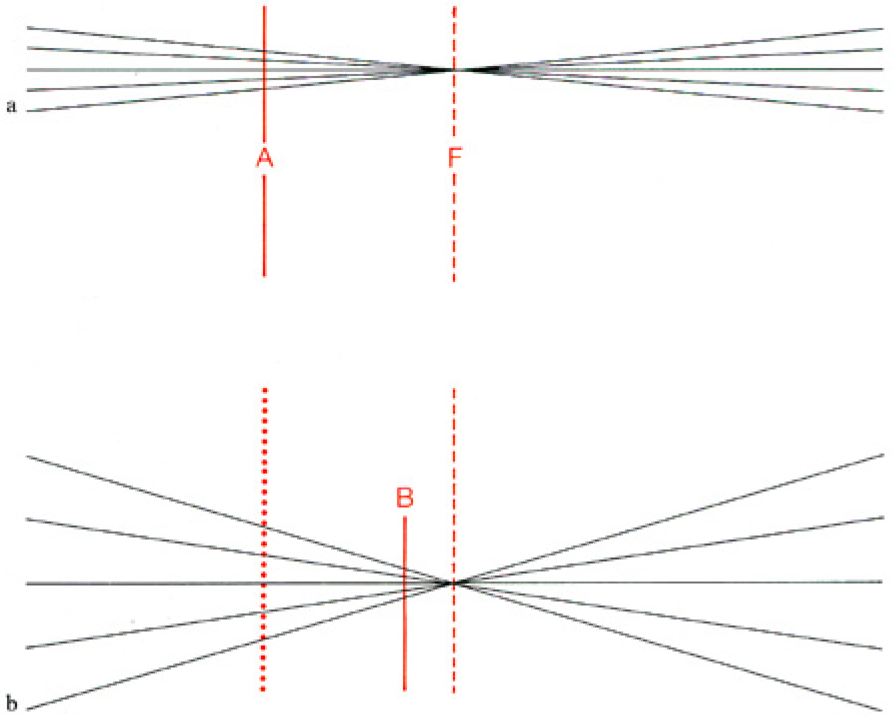


Fig. 2.154. **Energy density of light beams**

a In a weakly convergent beam, the energy density is still high some distance (*A*) from the focus (*F*).

b In a strongly convergent beam, the energy density falls rapidly with distance from the focus. Thus, the energy density at distance *A* is substantially lower than in Fig. **a**, and the site with the same density lies closer to the focus (*B*)

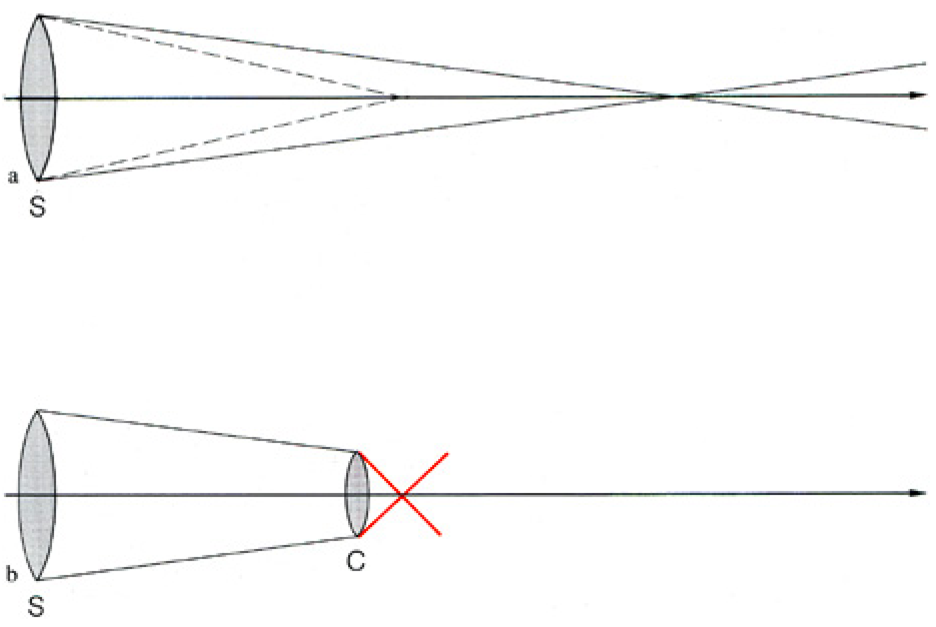


Fig. 2.155. **Focusing a light beam**

a Increasing the convergence of a light beam emerging from the optical system of an energy source (*S*) requires a reduction of the "working distance" between *S* and the focus (*hatched line*)

b Convergence can be increased further by placing additional optics (*C*) in front of the target (e.g., placing a contact lens with a convex surface on the corneal surface)

which defines the ideal wavelength for localizing the *site of action* to the desired layer. Monochromatic light is used for high-precision work. Polychromatic (white) light, containing a mixture of wavelengths, has different absorption spectra in various tissue layers.

The energy source for **application** of the light may have a linear or nonlinear mode of operation. In **linear** systems, increasing the energy of the light beam also increases its effect.[77] The amount of energy delivered to the tissue is easily controlled by adjusting the spot size and the power density ("intensity") of the light and the exposure time. When visible light is used, *monitoring* of the treatment can be done visually and is therefore simple and precise. Any optical barriers are easily recognized, and the effect is apparent.[78] If the *exposure time* is longer than the surgeon's reaction time, the various parameters can be adjusted as needed while the treatment is carried out.

Nonlinear effects can occur with energy sources whose *power* is increased by greatly compressing the energy in space and time. These sources deliver their power output in *pulses of several nanoseconds* duration or less.[79] There is no linear relationship between energy and response, for the latter is *threshold dependent*, i.e., no response occurs below the threshold, and the light continues to be transmitted past the focus. The response at or above the threshold consists of an explosive *optical breakdown* with associated

[77] Examples: Argon laser, crypton laser, Nd:YAG laser in the free-running mode.

[78] For example, coagulated protein is recognized by tissue discoloration, collagen shrinkage by tissue displacement, and over-treatment by the formation of vapor bubbles.

[79] Examples: Q-switched Nd:YAG laser in the nanosecond range, mode-locked Nd:YAG laser in the picosecond range.

back to index

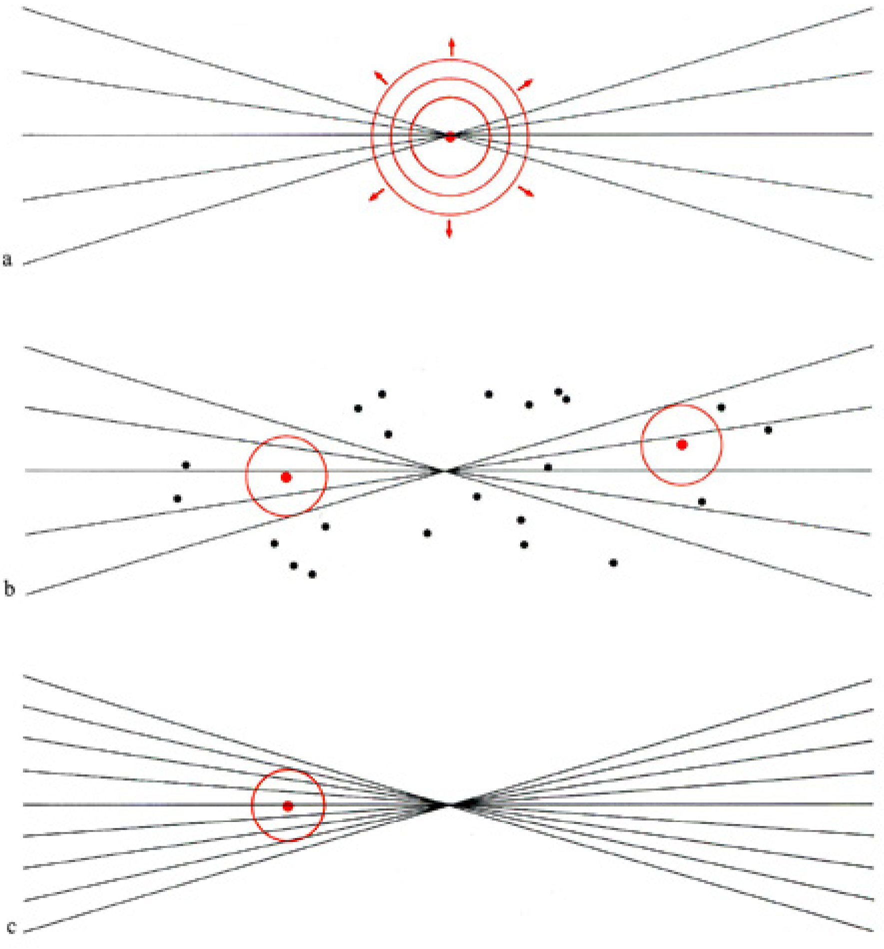


Fig. 2.156. **Optical breakdown**

a If the energy density at the focus reaches the threshold level for inducing ionization, optical breakdown follows. A plasma forms at the focus, and mechanical phenomena spread outward from that point in all directions.

b In an inhomogeneous medium with sites of lower threshold, optical breakdown can occur anywhere within the light beam.

c If energy input is increased, the energy density may reach the threshold level in front of the focus, and prefocal optical breakdown will occur at some point on the axis of the incident beam

thermal and mechanical effects (Fig. 2.156a).[80] Thus, nonlinear energy sources are suitable only for tissue division by the removal of material (see Fig. 2.51), provided it is acceptable for the tissue debris to remain within the eye.

Control is far more difficult with nonlinear energy sources than with linear sources, because the operator cannot influence events during the application. Rather, he must predict the effect in advance and adjust the power settings accordingly. This *prognosis* is based on "experience" and cannot be made with absolute confidence. The basic problem is that optical breakdown follows *statistical laws*. This means that the desired response may or may not occur at a given power output (Fig. 2.157). Thus, while the probability of a desired result can be estimated by statistical means, the exact result in a particular energy delivery cannot be predicted. The situation is further complicated by the fact that the threshold for a given clinical situation is unknown. Visible as well as invisible imperfections in the substrate (e.g., contamination by free electrically charged particles, surface irregularities on ocular media) can lower the threshold at some locations, allowing optical breakdown to occur at unanticipated sites anywhere within the beam (Fig. 2.156b). Increasing the energy output likewise can shift the effect away from the focus because energy densities may be produced in front of the focus that are high enough to precipitate optical breakdown (Fig. 2.156c).

So even with an optimum focusing technique, the operator cannot know precisely *when*, *where*, and *how strong* optical breakdown will be at the moment the pulse is emitted. He cannot know, in other words, whether the pulse will produce *no effect*, the *desired effect*, or *over-effect*. The best safety strategy for the use of pulsed lasers involves the maintenance of adequate *clearances*, i.e., performing laser coagulation only at sites where there is an adequate distance between the focus and structures that must be preserved.

Within the limits imposed by this safety strategy, we can set forth **technical and tactical guidelines** for the optimum utilization of nonlinear ophthalmic lasers:

The essential *technical* requirement is sharp focusing, accomplished by:

- eliminating sharpness-degrading "impurities" in the projected beam (having a beam of pure wavelength and mode);

[80] The thermal effects are coagulation or vaporization of the tissue. The mechanical effects are tissue destruction by acoustic and shock waves and other physical phenomena. The destructive effects are determined not just by the energy of a single pulse but also by the mode of pulse sequencing, e.g., the temporal emission pattern of pulses of uniform or variable intensity.

back to index

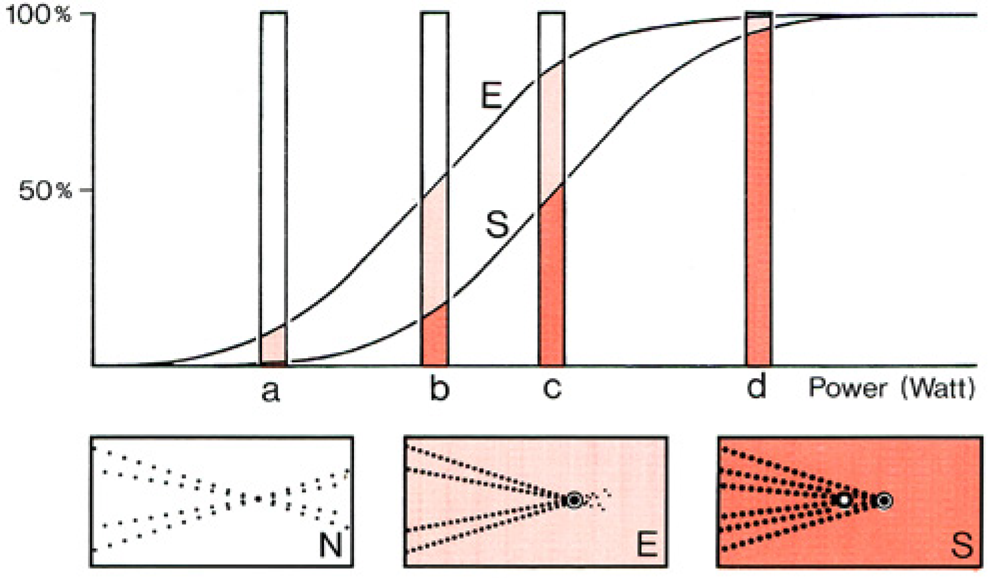


Fig. 2.157. **The statistical nature of optical breakdown**
N: No-effects: Full transmission of the emitted energy through the focus. There are only variations in energy density along the optical axis.
E: Desired effects: Optical breakdown occurs at the planned site (i.e., at the focus) and at the planned intensity.
S: Side-effects: Extrafocal and oversized breakdowns, causing damage to structures away from the target.
The curve shows the probability (in %) of the events *N*, *E*, and *S* to be expected at a given power output.

a Power below threshold for optical breakdown: While most of the deliveries will not produce optical breakdown, already some desired effects will occur, and rarely even some side-effects.

b Power at threshold for *E*: 50% of the deliveries will be desired effects, but there will be *N* as well, and even the danger of *S* increases.

c Power at threshold for *S*: 50% of the deliveries are side-effects. The majority of the other effects are *E*, but there are still *N*.

d Power above threshold for *S*: Besides *S* there are still some *E* and even *N*!

Note: The thresholds for *E* and *S* are not technically defined quantities but vary for every exposure, that is, at every new target (= new substrate) and after every delivery (= change of substrate). Thresholds, thus, are spatially and temporally unstable.
Practical significance: After observing the result of one delivery (at a given energy) it is impossible to predict the result of the next delivery (at the same energy output)!

- increasing beam convergence by use of convex contact lenses (see Fig. 2.155b).

From a *tactical* standpoint, the surgeon should employ methods that allow him to work gradually from a safety zone toward the target – this in terms of energy dosage as well as topography:

- The energy of the beam is low (subthreshold) initially and is gradually raised to the threshold level. Multiple applications are performed at each level due to the statistical nature of the optical breakdown effect.
- The beam is initially projected into a region where breakdown is harmless (safety zone) and from there is gradually moved toward the critical target region.
- Each time the energy level is raised, the beam is redirected toward the safety zone, and the approach maneuver is repeated due to the potential for optical breakdown outside the focus (see Fig. 2.156c).
- Treatment is discontinued when the cellular debris from previous optical breakdowns create nonhomogeneities in the substrate that pose a risk of extrafocal breakdown (Fig. 2.156b). Treatment may be resumed after sufficient time is allowed for spontaneous absorption and elimination of the breakdown products.

2.4 The Utilization of Chemical Effects (Electrolysis)

Direct current flowing between an active and indifferent electrode not only generates heat but also induces a *chemical reaction* involving the dissociation of electrolytes with the release of gas. In the process, alkali radicals incite a *colliquative necrosis* that occurs without significant tissue shrinkage, while acid radicals cause a *coagulation necrosis* with associated tissue shrinkage.

back to index