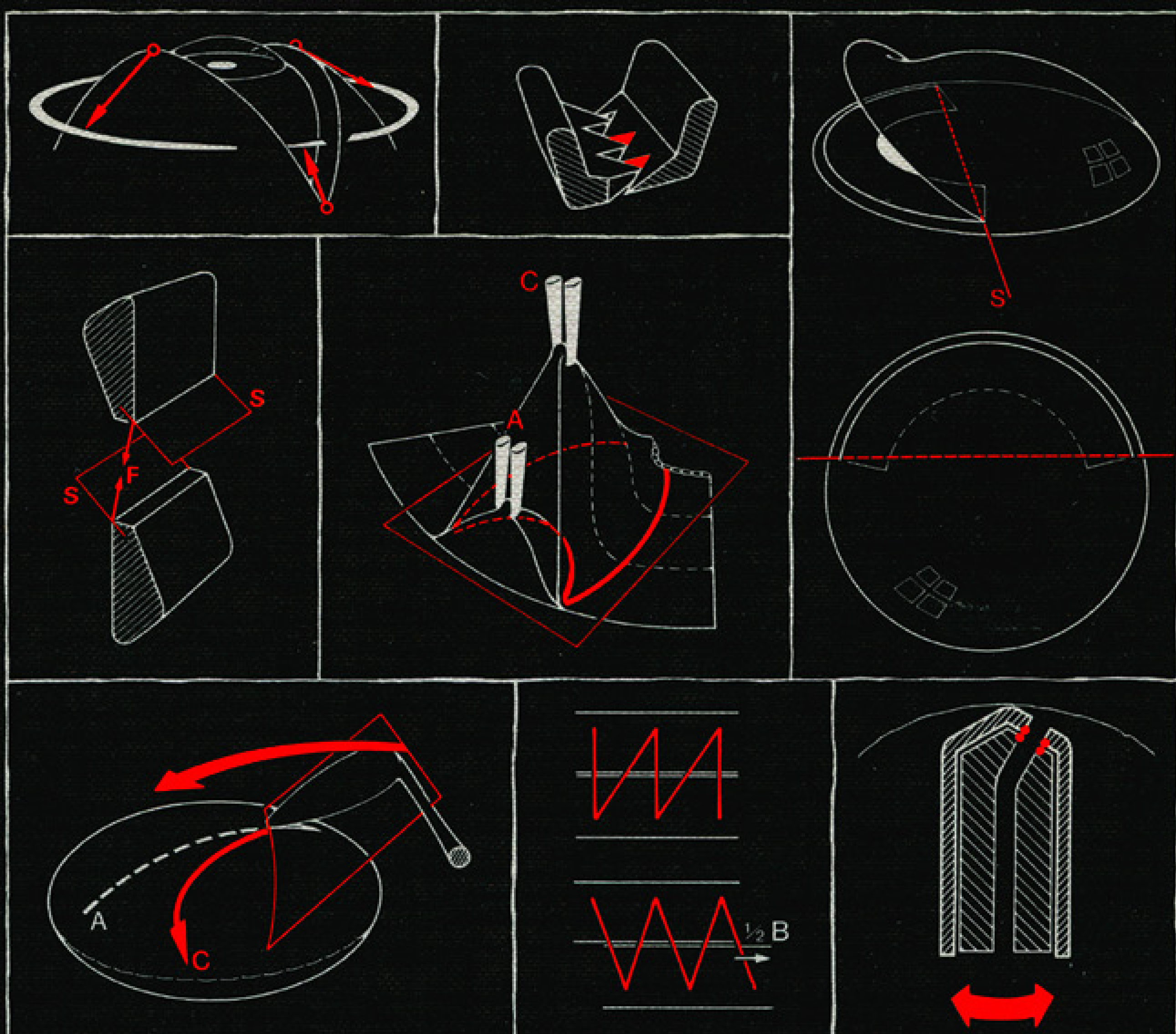
Georg Eisner

Eye Surgery

An Introduction to Operative Technique

Second, Fully Revised, and Expanded Edition



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Translated by Terry C. Telger

With 546 Figures, Mostly in Color
Drawings by Peter Schneider

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HANS GOLDMANN:

"... I am not manually skilled by nature,
so when it came to surgery I had to carefully ponder,
and try to understand rationally,
each step of the procedure ..."

(From a casual conversation)

PETER NIESEL:

Purely intuitive skills are difficult to analyze.
The underlying causes of success or failure remain obscure.
This may be why the operative methods
described by one author are often less successful in other hands:
While the method has been learned, the craftmanship has not.
Experience, dexterity and intuition are not conscious processes
and are thus difficult to transfer to others.
The present book is concerned with finding a rational basis
for specific surgical manipulations.

(From the introduction to the first edition of Eye Surgery 1978)

Preface

The second English-language edition of my book *Eye Surgery* is almost a new book. This reflects the developments during the ten years since the first manuscript was completed. Indeed, the changes have been so far-reaching that a fundamental different ophthalmic surgery has evolved. In the process, a new "way of surgical thinking" has emerged, calling for extensive revisions even in a book that is concerned with the elucidation of basic principles rather than with individual methods.

In keeping with modern developments, it has been necessary to add new chapters to this book and revise the old ones. The revisions took the author, working in his spare time, several years to complete.

While a book by one author has the advantage of being uniform in its style and presentation, it also has shortcomings due to the limitations inherent in a single-author work. It is my hope that, on the whole, the advantages will outweigh the shortcomings.

Though singly authored, the book would not have been possible without the help of others. It has thrived on the friendly exchange of ideas at our University Eye Hospital in Bern – an interchange that was already lively when the first edition was created, while Prof. Hans Goldmann was still clinical director, and which has been carried on by his successors. I am indebted to Prof. Peter Niesel, who based on his tireless research into causes and approaches offered important suggestions for the first edition and continued to offer helpful comments during the development of this second edition. Besides his daily support, he critically reviewed the first chapter on spatial tactics and helped to present the material with greater clarity and precision. I am grateful to Prof. Franz Fankhauser for reviewing the chapter on laser surgery. I also express thanks to the staff physicians and residents at our clinic, who by their useful questions and comments contributed many good ideas.

The number of illustrations has been expanded to 546. I was pleased to rely once more on the help of our university illustrator, Mr. Peter Schneider, who, in addition to his technical competence as an artist, displayed an insight and critical ability which clarified and enhanced my ideas. Although the new illustrations took a great amount of time and effort to complete, Mr. Schneider accomplished the job with patience and uncompromising accuracy. The reader will readily appreciate the quality of his work, a quality attested to by the fact that many of his drawings have since been reproduced in other books. I am very grateful to him.

I also wish to thank the translator of the German text, Mr. T.C. Telger. After his outstanding work on the first edition, I was greatly relieved to learn that he could undertake the job – a job made more difficult by the fact that the novel approach and new terminology in this book made it necessary to incorporate terms from other technical fields. Anyone familiar with the difficulty of reformulating complicated German syntax into readable English will appreciate his achievement.

My thanks go to Mrs. F. Meier-Gibbons MD and to Dr. Walter Lotmar for the careful proof-reading.

I express special thanks to my secretary, Ms. Christine Lehmann, for her tireless work in typing and retyping the text and its revisions. Her diligence and reliability were an important asset.

I also wish to thank Hans Grieshaber (Ophthalmic instruments Schaffhausen, Switzerland), Alcon Ltd. (USA), and Pharmacia AG (Uppsala, Sweden) for their financial support in the production of this book. Otherwise the many illustrations would have made the cost of the book prohibitive. With their assistance, it was possible to keep the didactic concept of the book intact.

I am again grateful to the staff at Springer Verlag for all their care and effort in the production of the book. They deserve recognition for the fact that the first German-language edition of *Eye Surgery* was listed among the 50 most beautiful German books by the Book Art Foundation of the Association of the German Book Trade.

Finally, I thank my wife Susanne and my children Daniel, Miriam, and Simone for their patience and understanding in accepting all the impositions upon family life that were inevitable during the creation of this book.

Bern G. EISNER

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Introduction

Eye Surgery is intended as a "grammar" of intraocular surgery. However, is such a grammar really necessary? Is it not better to learn by practice than by theory?

What is the role of grammar in learning a language? Indeed, there are people who learn by practice alone. However, while practice may be a fine way to acquire language skills rapidly for everyday use, it is a laborious way to acquire more sophisticated language skills. It is difficult to recognize and correct errors without a knowledge of the basic structure of the language. Furthermore, grammar makes it easier to acquire new knowledge because it facilitates the integration of newly learned material into a whole. Actually, grammar shortens the path to perfection.

In the same way, it is possible to learn surgery by practice alone. But the road to experience is long, and if this is true of routine procedures, it is even more true when it comes to dealing with complications, i.e., finding optimum solutions in unexpected situations. I do not believe that the trial-and-error quest for experience is compatible with the interests of the patient. A knowledge of surgical "grammar" shortens the learning process. Furthermore, it helps in comparing different methods and weighing their advantages and disadvantages. Finally, a mastery of grammar makes it easier to develop new methods, because the basic principles, once learned, can be applied to novel situations in which experience is necessarily lacking.

The present book is tailored to this "grammatical" way of thinking. It describes basic principles of operating technique rather than specific methods. Like a language grammar that is concerned less with what is said in the language than with how well it is expressed, *Eye Surgery* focuses not on *what* is done but on *how* something is done.

And just as the length of the paragraphs in a grammar book does not necessarily reflect the frequency of the problems ("the rules are usually shorter than the exceptions"), the lengths of the sections in this book do not correlate with the practical frequency of surgical situations. If selected problems are presented, they are merely examples intended for training the reader in a surgical way of thinking that will prove valuable in entirely different and perhaps unexpected situations.

Our grammatical approach is appropriate for the standard procedures in the anterior segment of the eye, which usually are performed on normal tissue in a normal anatomic position. For such tissues whose properties are reasonably predictable, the surgeon can rely on geometrical and physical principles. This applies much less in surgery of the posterior segment, however, where we are dealing with pathologically altered tissue that has been displaced from its original position. The primary concerns of the surgeon are the careful clinical evaluation of the pathology and the development of a strategy appropriate for that pathology. The "grammatical" aspects in this type of surgery play a minor role. Therefore, posterior segment surgery is not specifically treated in this book. However, a structured approach can be derived by analogy with the rules for surgery of the anterior segment, i.e., space-tactical requirements, instrumentation, the treatment of lamellar and elastic tissues, etc. When faced with pathology, it is the surgeon's task to recognize which of the respective rules are applicable and to find the best solution.

One point must be emphasized: Just as a grammar cannot replace a language textbook, this book is not meant to replace textbooks on ocular surgery. Here we tend to assume that the reader is already familiar with standard operative goals and methods; and when we do detail the steps in a specific procedure, it is only for the purpose of illustrating essential technical principles. A clinical evaluation of specific operations is outside our present scope.

Every learning process poses a dilemma: The whole cannot be known without understanding its parts, and the parts cannot be grasped without understanding the whole. A "grammar book" can be a helpful roadmap on this complicated path.

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The Paradox of High Success

Our goal in studying principles of surgical technique is to achieve the highest possible rate of success. Yet the closer we come to this goal, the more difficult it becomes to perceive the result of our efforts. The reason for this is what I call the "paradox of high success" – the curious fact that, as success rates improve, it becomes increasingly difficult to substantiate further improvements, because they become

- increasingly less apparent
- and increasingly difficult to prove.

The reason for the poor *perceptibility* of increments at high success levels stems from the practice of expressing success rates as percentages. However, the significance of a percentage change depends on whether it occurs at the middle or extreme end of the percentage scale. For example, a 10% improvement from 45% to 55% means very little, because both rates imply that there is roughly one success for every failure. Thus, the success rate (about 1:2) remains essentially unchanged despite the percentage improvement. In contrast, an improvement from 80% to 90% means that, where formerly we could expect about 5 successes for every failure, we can now expect about 10. In this case, then, the 10% improvement has led to a doubling of the success rate. Following this trend toward the extreme end of the scale, we will find that percentage improvements that appear negligibly small have a profound effect on the success rate. Thus, a rise of only 1% from 98% to 99% means that, where formerly we could expect 50 successes per failure, we can now expect about 100. A further improvement of only 0.5% beyond this point, from 99% to 99.5%, would be a tremendous advance, implying that only 1 in 200 patients would be at risk for failure.[1]

As the percentages rise, of course, there is a corresponding increase in the intellectual and material investment necessary to effect the improvement. Whereas little effort is needed to boost the rate from 45% to 55%, an increase from 80% to 90% calls for considerably greater know-how and technical expertise, while an increase from 99% to 99.5% demands a tremendous investment indeed. The basic problem is that, as success rates climb, it becomes increasingly difficult to justify the expense necessary for further improvements, since the improvement may not be amenable to statistical proof.

This brings us to part two of the "paradox of high success": the *unprovability* of extremely high success rates. The case numbers necessary for statistical proof increase dramatically with the success rate. For example, proof ($p < 0.01$) that a success rate of 80% has been raised to 90% by a new technique would require a data base of 250 cases. Proof of improvement from 98% to 99% would require about 2900 cases, and proof of a 99% to 99.5% increase would require about 5800 cases. Clearly, the case numbers necessary for a valid statistical study (one involving comparable patient populations, the same operator using a constant, standardized technique over the course of the study, and standardized follow-up procedures) cannot be achieved in practice. This implies that extremely high success rates cannot be proved.

I address this problem at the start of the book in the hope that the reader who seeks to optimize his surgical technique through intensive study will not become discouraged. Even though the results of his efforts may not be obvious or provable, the certainty of having done his best for the individual patient – *always the primary concern* – will still bring him satisfaction and will motivate him toward further refinements of his technique.[2]

[1] It follows that success rates are more easily appreciated when they are expressed as fractions.

[2] It is important for the surgeon to understand the paradox of high success not just for his own motivation, but also so that he can discuss the problem intelligently with political and administrative authorities who make funding decisions. Obviously it is difficult to justify the enormous costs of increasing a high success rate when the improvement is neither numerically impressive nor provable.

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Tactics in Ophthalmic Surgery

Modern microsurgery has revolutionized the conduct of eye operations. Above all, it has changed the mode of *feedback* on which the surgeon relies to guide his manipulations. The classic concept of *tactile feedback*, in which the operator is guided by tissue resistance, has been largely superseded by a *visual feedback* that relies on the evaluation of spatial relationships. With tissue resistance no longer a critical factor in guiding the application of forces, it has been possible to develop finer instruments that are more in line with the demands of atraumatic technique.

But modern ophthalmologic microsurgery implies more than improved visualization and finer instrumentation. It embodies an entirely new approach to *surgical tactics* in general. The way of "classical" surgery is to accomplish a given task in a minimum number of steps, with each step achieving as many individual goals as possible. The success of this "synthetic" approach requires extremely high skill and dexterity on the part of the operator.[1]

This contrasts with the "analytical" approach of the microsurgical technique, which permits every surgical action to be broken down into its individual components. The advantage of this approach is that each step can be adapted to a specific situation, making it easier for the surgeon to deal with any complications that arise.[2]

Microsurgical technique, then, is characterized by an *increased number of individual manipulations*. While this has advantages, it also increases the potential for tissue lesions caused by inadvertent movements of instruments or tissues. Consequently, modern microsurgery is concerned not just with the intended effects of a surgical action (*offensive tactics*) but also with the

Table 1. **Surgical tactics in ophthalmology**

	Tactical goals	Targets of surgical action	Instruments
Tissue tactics	Division, Removal, Uniting } of tissue	Cornea Iris Lens Vitreous Retina	– Knives – Forceps – Sutures
Surface tactics	Protection of surfaces	Endothelium Lens capsule Anterior hyaloid Inner limiting membrane	– Viscous materials – Plastic sheeting
Spatial tactics	– Maintenance or expansion of intraocular compartments – Blockade of connecting pathways	Intraocular chambers and subcompartments	– Hydrodynamic flow systems – Viscoelastic materials – Bubbles with surface "membranes" (gas, oil)

[1] Examples of "synthetic" manipulations:

- The anterior chamber is opened in a single maneuver with a cataract knife or keratome. The incision requires simultaneous rotational movements about various points and thrusting movements of extreme precision (see Fig. 5.48). The slightest error will jeopardize the procedure by allowing premature collapse of the anterior chamber. The result is a unique type of incision profile; modifications and corrections are nearly impossible.
- Anterior capsulotomy with a forceps (see Fig. 8.44) excises and removes a piece of the anterior capsule whose size and shape are difficult to control. The slightest error may result in an inadequate capsulotomy, rupture of the posterior capsule, damage to the zonule, or unintended extraction of the whole lens.

[2] Examples of the "analytical" approach:

- By opening the anterior chamber with step incisions made on multiple planes, the surgeon can accurately control the shape and profile of the incisions (see Fig. 5.62) and modify them as needed. Each step requires special manipulations, but errors in previous steps can be corrected in subsequent steps, providing an increased margin of safety.
- Anterior capsulotomies can be performed in multiple "ministeps" (see Fig. 8.38) to create an opening of any desired shape and size. With each new step the surgeon is able to correct errors made in previous steps.

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avoidance of undesired side-effects on the surrounding tissues (*defensive tactics*).

Offensive tactics, also referred to as **tissue tactics**, include such actions as the grasping, division, removal, and uniting of tissues. The instruments used for these actions are forceps, knives, sutures, etc.

Defensive tactics may be subdivided into surface tactics and spatial tactics. **Surface tactics** are *passive* defensive measures in which protective materials such as plastic film or viscous substances are used to keep tissue surfaces from coming in contact with instruments, implants, or other tissues. **Spatial tactics** are *active* defensive measures in which surrounding tissues are protected by *maintaining or augmenting tissue spaces* to create sufficient room for the numerous micromanipulations. This can be accomplished by the use of hydrodynamic systems, viscoelastic materials, or "membranous implants" (Table 1).

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1 Spatial Tactics

Spatial tactics in ophthalmic surgery are concerned with the shape and volume of the globe and its interior compartments (Fig. 1.1). The objective is to alter these parameters or maintain them in a controlled way during the application of external forces. Spatial tactics provide the immediate context within which the cutting, removing, and uniting of tissues are performed.

The **shape of an intraocular chamber**, and thus its volume, is a function of its *wall tension*. This tension results from the physical properties of the wall tissue and/or from the pressure inside the chamber. For a given tissue, then, a change in the volume of the chamber is associated with a change in its internal pressure.

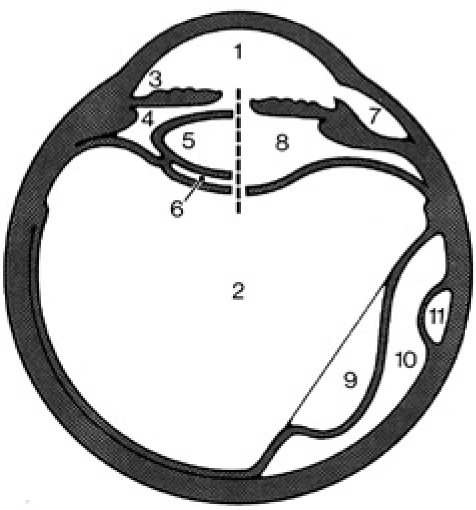

Fig. 1.1. **The globe and its compartments**
Left side: Normal anatomy
Right side: Pathologic spaces

Closed chamber systems:
1 Anterior chamber
2 Vitreous chamber

Open subcompartments:
3 Iridocorneal sinus
4 Iridocapsular interspace
5 Intercapsular sinus
6 Hyalocapsular interspace
7 Cilioscleral interspace (after cyclodialysis)
8 Iridohyaloid interspace (after intracapsular cataract extraction)
9 Vitreoretinal interspace (after posterior vitreous detachment)
10 Chorioretinal interspace (after retinal detachment)
11 Sclerochoroidal interspace (after choroidal detachment)

1.1 Pressure Systems for Regulating Chamber Volume

A *pressure system* is illustrated in Fig. 1.2. The pressure in a chamber P_{ch} is determined by the relation between the inflow volume (V_{in}) and the outflow volume (V_{out}). The pressure in the chamber will remain constant as long as the inflow and outflow volumes are equal (formula 4). However, the pressure cannot be set to a predetermined level just by stipulating the flow-through parameters because it is a ratio and, as such, P cannot be expressed in isolation from the other parameters in formula 5. A given pressure can be established and maintained only by a regulating system which measures the chamber pressure and uses the measured pressure as feedback to make appropriate adjustments.[1]

Of practical importance are the *extreme values* that can develop in a pressure system and the conditions under which they occur (formula 6): The highest pressure is the initial pressure (P_{start}), and the pressure inside the chamber approaches that value when the inflow resistance tends toward zero or the outflow resistance tends toward infinity.[2] The lowest pressure is the ter-

[1] In the absence of such a measuring system, one must rely on an "adequate" pressure as determined by visual observation of the chamber volume.
[2] As a practical example, the occlusion of a tightly inserted outflow cannula would produce an infinite outflow resistance.

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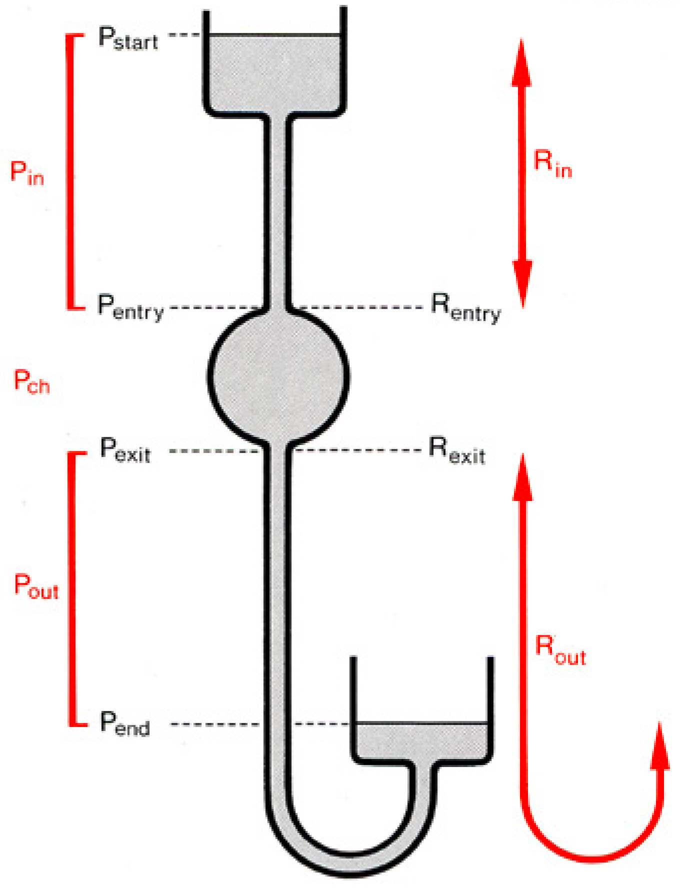

Fig. 1.2. **Schematic diagram of a system for regulating pressure in a chamber.** *Top*: inflow line. *Center*: chamber. *Bottom*: outflow line

[1] Inflow pressure $P_{in} = P_{start} - P_{entry}$
Outflow pressure $P_{out} = P_{exit} - P_{end}$

[2] Chamber pressure $P_{ch} = \frac{P_{entry} + P_{exit}}{2}$
for small differences between P_{entry} and P_{exit}: $P_{ch} = P_{entry} = P_{exit}$

[3] Volume of inflow $V_{in} = \frac{P_{in}}{R_{in}}$
Volume of outflow $V_{out} = \frac{P_{out}}{R_{out}}$

[4] $V_{in} = V_{out}$ when $\frac{P_{in}}{R_{in}} = \frac{P_{out}}{R_{out}}$
or $\frac{P_{in}}{P_{out}} = \frac{R_{in}}{R_{out}}$

[5] Inserting [1] and [2] into [4]:
$\frac{P_{start} - P_{ch}}{P_{ch} - P_{end}} = \frac{R_{in}}{R_{out}}$

[6] Therefore:
when $R_{in} \to 0$, then $P_{ch} \to P_{start}$
when $R_{in} \to \infty$, then $P_{ch} \to P_{end}$
when $R_{out} \to 0$, then $P_{ch} \to P_{end}$
when $R_{out} \to \infty$, then $P_{ch} \to P_{start}$

minal pressure (P_{end}). It develops in the chamber when the inflow resistance tends toward infinity or the outflow resistance tends toward zero.[3]

When values are selected for the **initial pressure** and **terminal pressure**, it must be considered that these extreme values can indeed develop in the chamber under extreme conditions, so they should remain within limits that can be tolerated by the chamber.

In selecting the **inflow resistance**, very low values are advantageous because they permit the selection of a low initial pressure.[4] On the other hand, a high value is advantageous for the **outflow resistance**, as this makes it easier to stabilize the chamber volume. Free selection of the outflow resistance is limited by the fact that surgical goals prescribe minimal widths for openings. Thus, when planning the pressure system for a particular procedure, the surgeon should first define the outflow resistance and then adapt the other parameters to that value.

In surgical practice, then, the various types of **space-tactical system** that are utilized to control the shape and volume of intraocular spaces are classified according to their outflow resistance:

- systems in which the outflow resistance is so high that, under ordinary conditions, there is no drainage of the chamber contents, and no inflow is needed to maintain the chamber pressure (*no-outflow systems*, Fig. 1.3a);
- systems in which the outflow resistance is within limits that allow the pressure to be controlled by regulating the inflow and outflow (*controlled-outflow systems*, Fig. 1.3b);
- systems in which the outflow resistance is so low that a given inflow system is incapable of pressurizing the chamber (*uncontrolled-outflow systems*, Fig. 1.3c).

[3] As practical examples, the inflow resistance approaches infinity when the inflow tubing is inadvertently bent; the outflow resistance tends toward zero when an outflow orifice is widely opened.

[4] As we will see later, however, low values are problematic when external forces act on the chamber. Limits are imposed as well by topographic factors (the size of the cannula).

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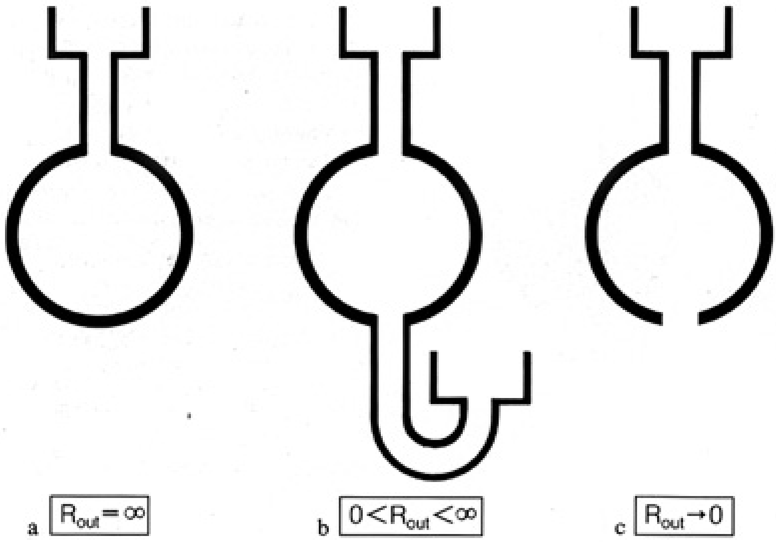

Fig. 1.3. **Space-tactical systems**

a No-outflow system: As outflow resistance tends toward infinity, no drainage occurs, so there is no need for inflow.

b Controlled-outflow system: The outflow resistance is finite and greater than zero. The available inflow capacity can compensate for the outflow.

c Uncontrolled-outflow system: As outflow resistance tends toward zero, the pressure in chambers open to the outside approaches atmospheric (=0)

1.1.1 No-Outflow Systems

No-outflow systems are technically straightforward. **Primary no-outflow systems** are those in which the contents of the chamber remain unchanged (Fig. 1.4.a, b). It is necessary only to introduce instruments into the chamber in such a way that the access opening remains *watertight*. Surgical options are limited, however, since no material may be removed from the eye, and such systems are suitable only for procedures involving the division of tissues.[5] Absolute no-outflow systems are procedures performed with lasers.

In **secondary no-outflow systems** the chamber is filled with a highly *viscous material* (Fig. 1.4c). Since the size of the outflow opening is not a critical concern in this system, bulky instruments and implants may be introduced into the chamber, and tissue fragments may be removed. Actually, uncontrolled-outflow systems can be converted to secondary no-outflow systems by filling the chamber with viscous material.

1.1.2 Controlled-Outflow Systems

The controlled-outflow system is a **regulating system** that uses a feedback mechanism to coordinate inflow and outflow. Theoretically it would be ideal to have an inflow capacity large enough to compensate for any outflow that might occur. In practice, however, there are constraints: Once the inflow limit is reached it becomes necessary to reverse the control mechanism and regulate the outflow so that it does not outstrip the available inflow capacity. With resistance-modulated outflow, the inflow capacity limits the permissible size of the outflow opening (Fig. 1.5a). With pressure-modulated outflow, this capacity limits the permissible level of the suction (Fig. 1.5b).

Controlled outflow systems imply that inflow ceases when outflow is obstructed. If continuous flow is required because the infusion must perform functions in addition to volume control (e.g., cooling an ultrasonic vibrator or a coagulator), it is essential to avoid total obstruction of outflow. This danger can be eliminated by providing a second, reserve outflow path in addition to the controlled-outflow path (Fig. 1.5c).[6]

1.1.3 Uncontrolled-Outflow Systems

If the inflow capacity is not adequate for a given outflow, the chamber volume can no longer be pressure-modulated. This is the case when there is a large chamber opening, whose lack of outflow resistance would require an inflow capacity of infinite size (Fig. 1.6a). In a chamber that has no inflow system, even the slightest leak will produce a state of uncontrolled outflow (Fig. 1.6b).

[5] Such as capsulotomies, iridotomies, and synechiotomies.

[6] This is the case in phacoemulsification, where a deliberate "leak" is left in the corneoscleral opening next to the irrigating tube to ensure an uninterrupted flow of cooling liquid.

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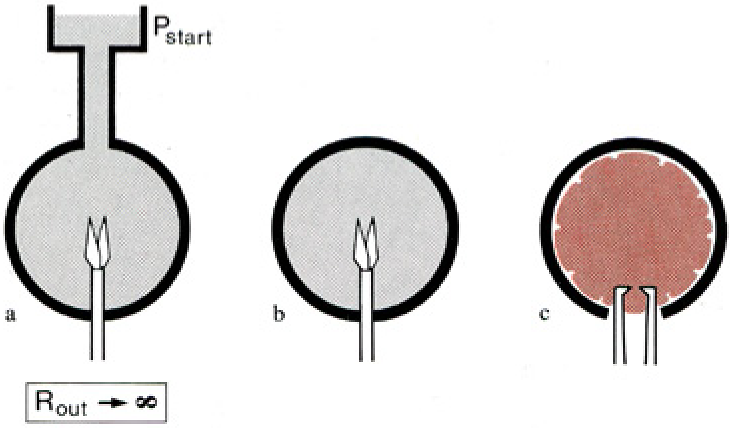

Fig. 1.4. **No-outflow systems**

a, b Primary no-outflow system: The high outflow resistance is based on the size of the outflow opening. A seal is obtained by adapting the opening to the instrument diameter.

a An inflow line may be connected to the chamber to alter its pressure (the initial pressure P_{start} becomes the chamber pressure).

b If just the existing chamber pressure is to be maintained, no inflow is required.

c Secondary no-outflow system: The high outflow resistance is based on the high flow resistance of the chamber contents, i.e., the chamber is filled with a material that cannot drain because of its high viscosity

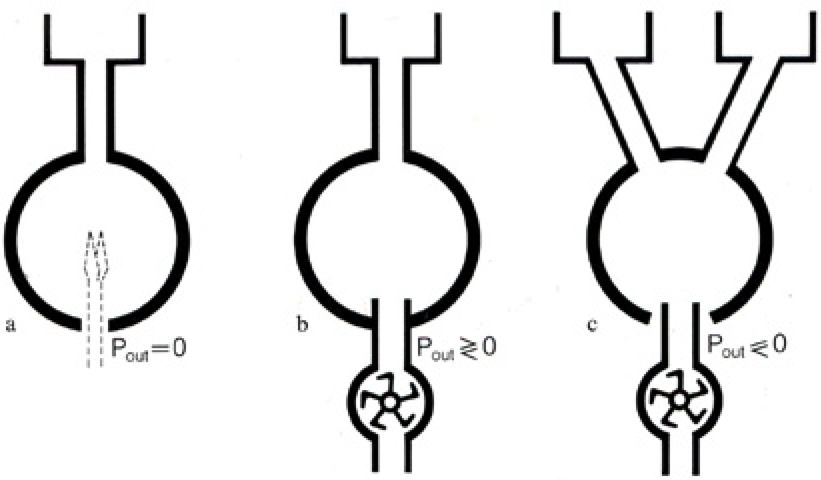

Fig. 1.5. **Controlled-outflow systems**

a Modulation of resistance: Outflow is controlled by modulating the resistance to drainage through a leaking outflow orifice. The necessary inflow capacity depends on the size of the leak at the outflow orifice, which should not be opened to a degree that would outstrip that capacity. The outflow pressure is constant (atmospheric pressure).

b Modulation of pressure: Outflow is controlled by a cannula whose junction with the chamber is watertight. The necessary inflow capacity depends on the negative pressure (suction), which should not be low enough to outstrip that capacity. The outflow resistance is constant (length and caliber of aspiration cannula).

c Combined modulation of pressure and resistance: The opening around the aspiration cannula is not watertight. Control is made more complex by parallel outflow paths, which are partly pressure-modulated and partly resistance-modulated. A correspondingly large inflow capacity is required, and a second inflow line may be advantageous

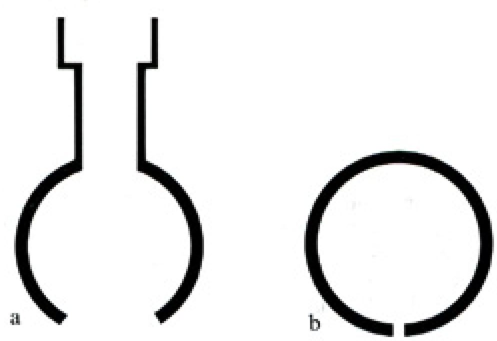

Fig. 1.6. **Uncontrolled-outflow systems**

a When the outflow resistance tends toward zero, infinite inflow would be needed to pressurize the chamber.

b If no inflow is supplied ($P_{in}/R_{in}=0$), even the slightest wound leak R_{out} will allow uncontrolled drainage

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1.1.4 Effect of External Forces on Regulating Systems

The principle that a particular chamber volume correlates with a particular pressure and can be stabilized by maintaining that pressure is valid only as long as the pressure surrounding the chamber remains unchanged. If the ambient pressure rises, the pressure inside the chamber must also rise by a certain amount to maintain a constant volume.

It is not enough, then, to determine how effectively regulating systems can maintain a specified pressure. We must also determine how they behave in response to the application of external forces.

In chambers whose shape depends on pressure, the pressure inside the chamber will rise when its wall is deformed (Fig. 1.7).[7] If outflow from the chamber is possible (i.e., if the outflow resistance is finite), a portion of the chamber contents will gradually discharge. The pressure will fall until it again reaches the level imposed by the regulating system. This implies, however, that the chamber has lost some of its volume and has become deformed.

The rate at which this loss occurs is of practical importance. If the

[7] The extreme case being a spherical chamber, where any deformation causes a volume change and even the slightest deformation raises the pressure (see Fig. 1.41).

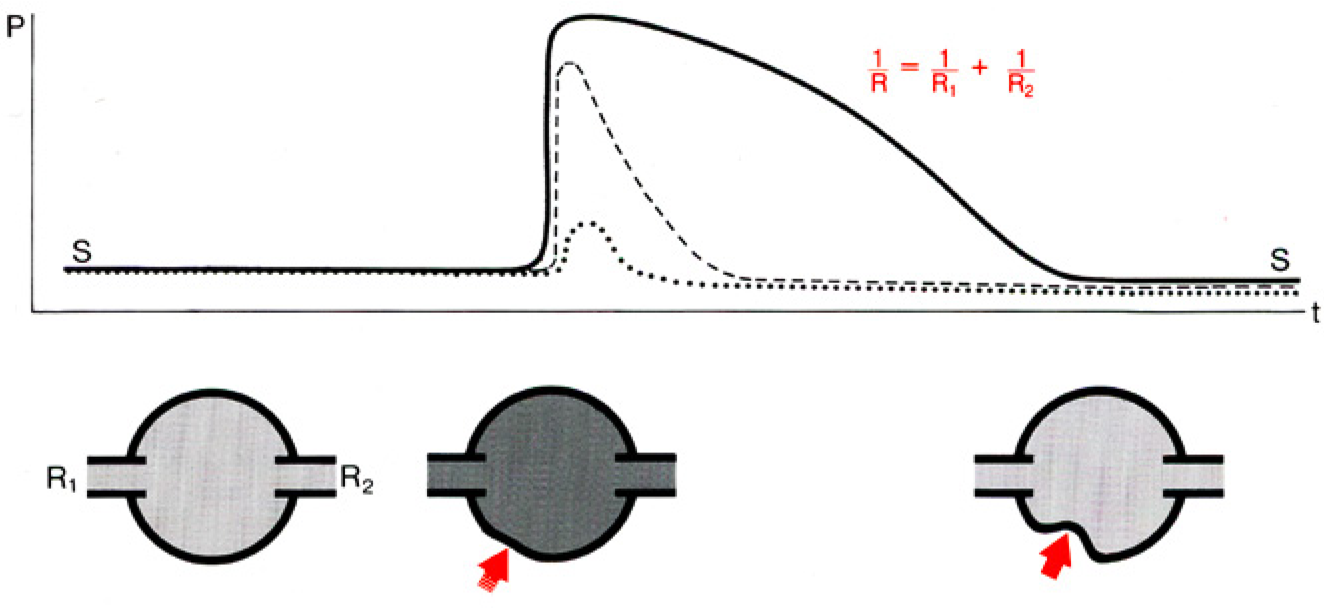

Fig. 1.7. **Response of space-tactical systems to external forces**. When the pressure in the chamber rises in response to external forces, outflow is increased until the pressure returns to the steady-state level imposed by the regulating system (*S*). Meanwhile the chamber is deformed, with maximum deformation occurring in the steady state. The outflow rate (for a given total elasticity) depends both on the level of the outflow resistance and on the inflow resistance

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volume loss is abrupt, the surgeon has insufficient time to react. The safest systems, then, are those in which the pressure reacts very slowly in response to external forces.[8]

The critical factor in this regard is the *outflow resistance* from the chamber. The lower the resistance, the more rapid the volume loss. This loss is most rapid in an *uncontrolled outflow* system, where an applied force causes immediate deformation of the chamber. In a *no-outflow* system, on the other hand, the force causes only a rise in pressure. In a *controlled-outflow* system the rate of volume loss depends on the openings that are available for outflow. But in evaluating outflow, it should be realized that a primary inflow opening can become an outflow opening when the chamber pressure rises. This means that low inflow resistances are advantageous in a controlled-outflow system only when they serve to correct for pressure fluctuations. They are disadvantageous under the action of external forces because they make the system susceptible to volume loss.

1.1.5 Basic Safety Strategy for Spatial Tactics

The *dilemma* in pressure-regulating systems is that the maintenance of a given pressure can ensure a constant chamber volume only as long as the environment is stable, but that maintenance of the given pressure means loss of volume from the chamber as soon as external forces are applied. Thus, if a system is chosen that is extremely fast in responding to pressure changes, it will also be very sensitive to external forces. This is taken into account in the **basic spatial safety strategy**: Optimum spatial stabilization is achieved by a control system that maintains a constant pressure by responding quickly to pressure fluctuations within the chamber (*intrinsic factors*). The problem of susceptibility to external forces (*extrinsic factors*) is solved by implementing measures to protect the chamber from the action of those external forces.

In the chapters that follow we shall describe first the space-tactical instruments that can be used to control intrinsic factors, and later we shall consider means for preventing the deformation of chambers by extrinsic factors.

1.2 Space-Tactical Instruments

Intraocular spaces can be maintained or expanded by the use of substances which, when introduced through a small access opening, can occupy a large volume inside the chamber, i.e., implants that can be injected through thin cannulas:

- *watery implants*, whose flow resistance depends chiefly on external friction, i.e., on the wall properties of the flow system;
- *viscous and viscoelastic implants*, which create resistance through high internal friction; and
- *"membranous" implants (bubbles)*, whose efficacy is based on surface tension.

[8] Even when the globe is intact, external forces cause the intraocular volume to change. But aqueous drainage through the corneoscleral trabeculum occurs against such a high resistance that external deformation is effective only when sustained for a long period (e.g., scleral buckling in retinal detachment surgery).

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1.2.1 Watery Fluids

Properties

Watery fluids have an extremely high molecular mobility and extremely low internal resistance. Even the slightest external force will cause displacement of the fluid.

The initial and terminal pressures of the fluid are determined by the **pressure sources**. In *gravity systems* they are determined by the height of the water column, which of course is limited by available space. *Pumps* can generate very high pressures, which require valves for their control (Fig. 1.8).

The initial and terminal pressures are extreme values. They cannot be used to calculate the pressure inside the chamber (see Fig. 1.2). If there is no precise regulating system, the surgeon's only option is to rely on "experience" for determining and maintaining the desired chamber pressure. But this experience is valid only for a particular system whose parameters are strictly maintained. One has to be aware of *disturbing factors* which alter pressures and resistances in unforeseen ways, causing the actual chamber pressure to deviate from empirical values. The *pressure*, for example, can be influenced by elastic phenomena associated with the presence of air bubbles or the use of soft elastic tubing. A change of pressure in the system can cause elastic energy to become stored and subsequently released, with corresponding effects on the shape and volume of the chamber (Fig. 1.9). **Flow resistances** in the system are subject to Poiseuille's law.[9] This

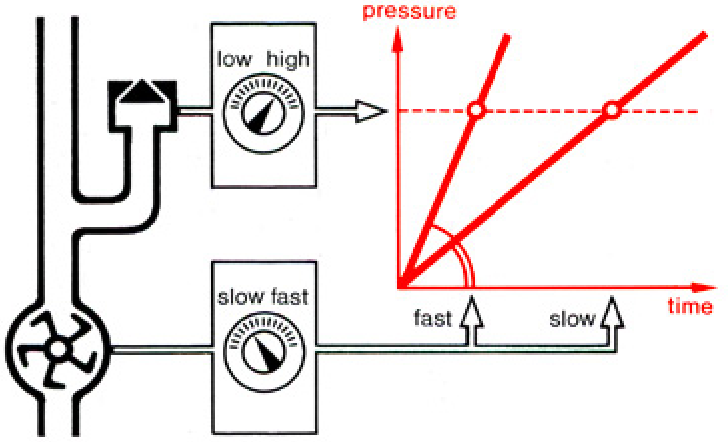

Fig. 1.8. **Control of pump-driven fluid transport systems**. The pressure level is limited by a valve and can be raised or lowered by adjusting the pressure dial. The speed at which this pressure level is attained depends on the delivery rate of the pump, which is controlled by the velocity dial

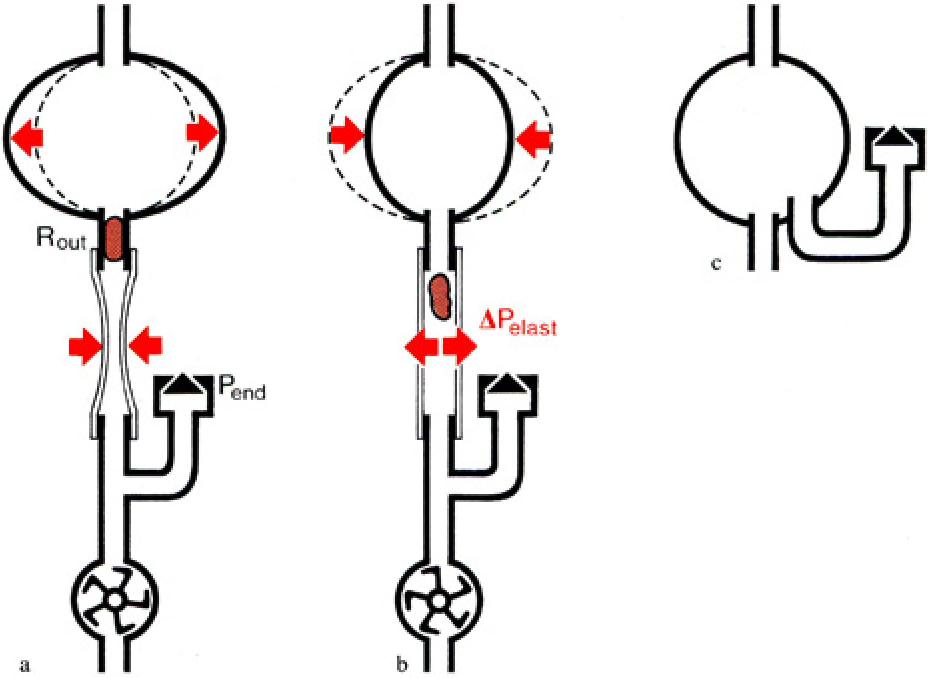

Fig. 1.9. **Effect of soft elastic tubing on pressure control**

a When a particle becomes lodged in the outflow cannula, the outflow resistance R_{out} rises precipitously. The pressure in the chamber approaches the initial pressure P_{start}, and the chamber wall expands. The pressure in the outflow tube falls, approaching P_{end}. But when this pressure, which is set by the valve, is reached the walls of the tubing have contracted (thereby storing elastic energy).

b When the obstruction is cleared, the pressures would return to the preset levels if the tubing were rigid. But with soft elastic tubing, the previously stored elastic energy is abruptly released and briefly augments the suction, causing a precipitous, unplanned pressure drop in the chamber.

c For reliable pressure stabilization, the valve should be connected directly to the chamber

[9] Poiseuille's law: $R = c \cdot \frac{\eta \cdot L}{r^4}$
R = resistance
η = fluid viscosity
L = length of flow path
r = radius of lumen
The law applies to ideal fluids. For real fluids, the resistances increase by a significantly greater amount when the radius is decreased.

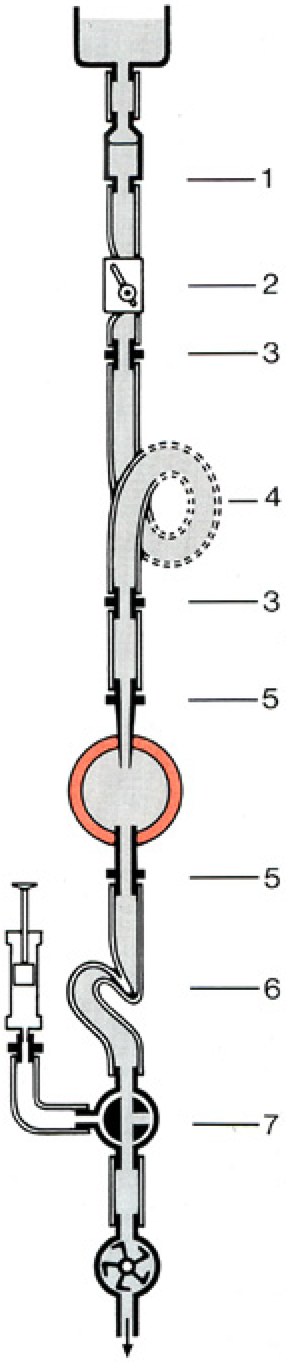

Fig. 1.10. **Sources of increased resistance in the fluid transport path**

1. Connector between tubing and drip chamber
2. Clamp-type flow regulator
3. Tubing connectors
4. Redundant extension tubing
5. Cannula
6. Kink in tubing
7. Connectors and lumina of three-way stopcock

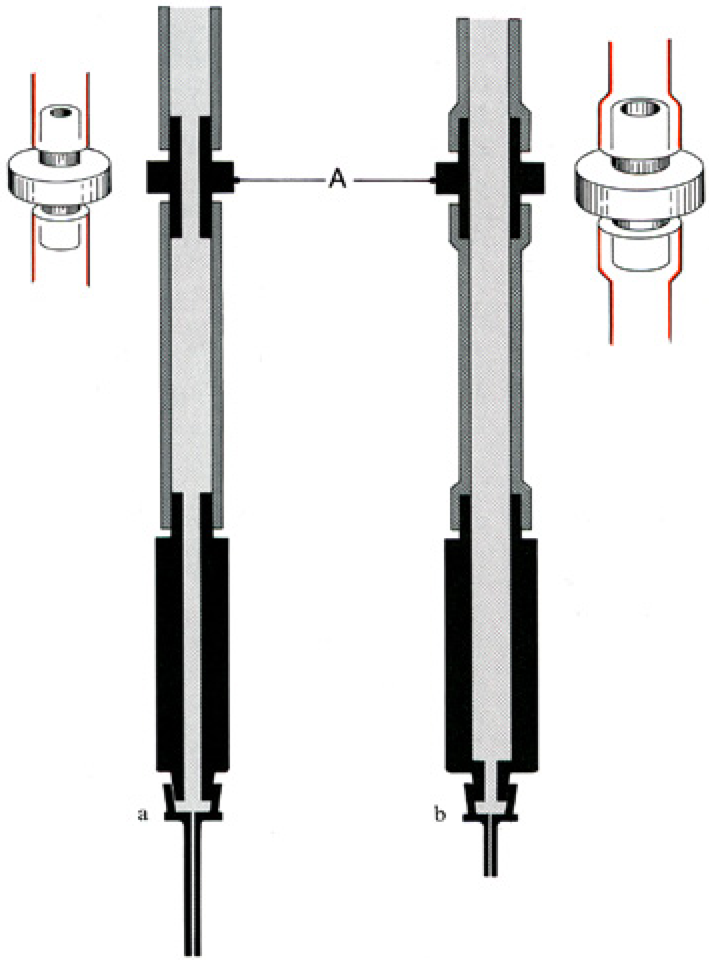

Fig. 1.11. **High- and low-resistance transport systems**

a *High-resistance system:* The tubing connector (*A*) and the handle of the cannula have a smaller inside diameter than the tubing itself. Therefore, in this arrangement the ends of the flexible tubes are not expanded at their connections with the rigid tubes.

b *Low-resistance system:* The lumen remains constant und unconstricted as far as the inlet of the cannula. Therefore, the ends of the flexible tubes must expand at the connections. The lumen of the handle should be wide, but this is not apparent from external inspection and must be checked before the equipment is procured. The cannula should be as short as possible to decrease resistance

law states that resistance to fluid flow through a tube is proportional to the length of the tube and inversely proportional to the fourth power of its radius. Thus, doubling the length of the tube increases the resistance two-fold, while halving its radius increases the resistance 16-fold. It follows, then, that even slight reductions in cross-section will greatly reduce the volume rate of flow (Fig. 1.10). Unnecessary constrictions should be avoided in a fluid transport system, and if such constrictions are necessary due to space limitations (e.g., cannulas inserted into the eye), they should be kept as short as possible (Fig. 1.11).[10]

[10] Because computational means are not available for evaluating an optimally balanced fluid transport system, the system should be tested beforehand on a phantom chamber whose wall characteristics are like those of the chamber to be protected. In that way the response of the system to disturbances (e.g., obstruction of a tube and storage of elastic energy) can be tested and optimally adjusted.

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Application of Watery Fluids

Watery fluids are distributed rapidly to all parts of the chamber, regardless of their site of introduction. Thus, cannulas do not have to be inserted deep into the chamber, and the conditions at the entry site are the only critical factor from the standpoint of spatial tactics.[11]

Resistance parameters relating to **instrument geometry** are not variable and depend on *cross-sectional dimensions:* lumen and external shape (Figs. 1.12 and 1.13). The **position of the cannula** at the entry site is variable, however. *Raising* or *lowering* the cannula reduces the outflow resistance, whereas *swiveling movements* of the cannula in a lateral direction increase it (Fig. 1.14). Thus, these movements are an important means by which the surgeon can regulate outflow resistance. On the other hand, movements of this kind can have significant adverse effects when performed inadvertently, especially when they are unnoticed by the operator. *Monitoring of the cannula position at the entry site*, then, is the most important safety measure for the application of watery fluids in spatial tactics.

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[11] The direction of fluid flow is immaterial from the standpoint of spatial tactics. However, if the fluid stream is used to achieve tissue-tactical goals (mobilization and transport of tissue particles), the position of the cannula tip is critical. This is discussed more fully in Figs. 2.18 and 2.23.

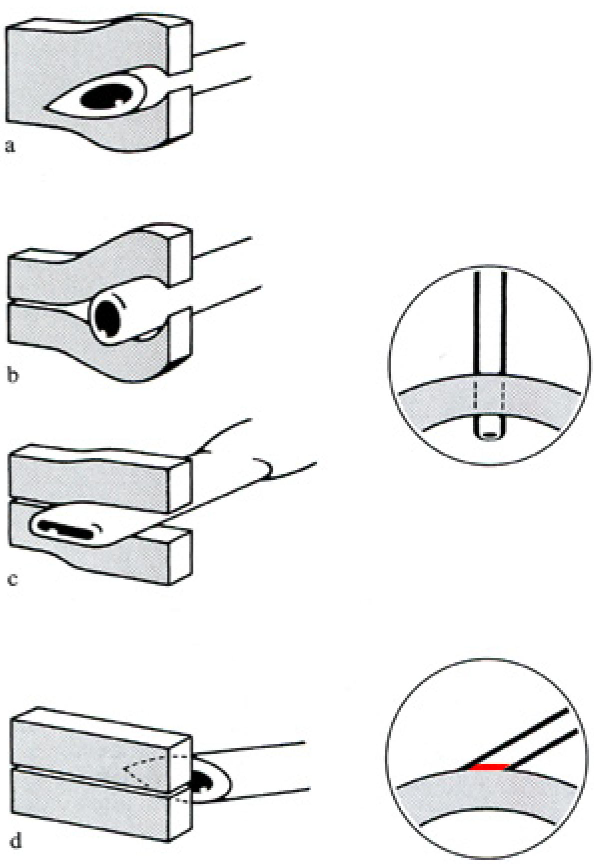

Fig. 1.12. **Methods of sealing the access opening with simple cannulas**

a When a cannula with a sharply beveled tip is thrust directly through the tissue it creates an opening that conforms exactly to the outside diameter of the cannula. Leakage does not occur.

b When a cylindrical cannula is inserted through a stab incision, the cross-sections of the cannula and incision are incongruent, and the opening around the cannula is not watertight.

c A flattened cannula conforms better to the incision and permits less leakage.

d When a cannula with a sharp bevel is applied to the incision such that its entire rim apposes snugly to the tissue, the injected fluid will itself open the incision, and the opening will conform exactly to the cross-section of the stream. It remains open only while the stream is maintained, and reflux cannot occur.

Note: Whereas the cannula is perpendicular to the tissue surface in **a**, **b** and **c** (*inset top*), the cannula in **d** is applied at an angle equal to the bevel angle of the tip (*inset bottom*)

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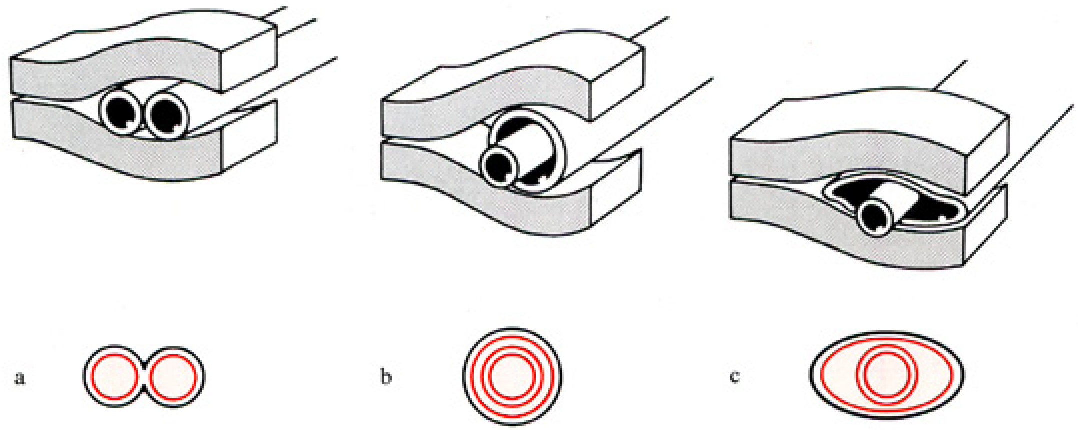

Fig. 1.13. **Double cannulas for infusion and aspiration.** Below the perspective drawings are cross-sectional diagrams in which the surfaces that critically affect flow resistance are shown in *red*. Inflow resistance depends chiefly on the lumen of the infusion cannula, while outflow resistance depends on both the lumen and external shape of the aspirating cannula.

a Parallel arrangement: Both cannulas are cylindrical with equal ratios of lumen to surface area. The total external cross-section of this arrangement is analogous to that in Fig. 1.12c.

b Coaxial arrangement: Fluid is infused through the outer tube and aspirated through the inner tube. The surface area bordering the stream in the outer tube is twice that in a circular lumen of equal diameter, creating a correspondingly high infusion resistance. Hence, the diameter of the outer tube must be relatively large to allow for an adequate infusion capacity, thus accentuating the problem of leakage around the tube (analogous to Fig. 1.12b).

c Coaxial arrangement with a soft outer sheath: Since the compliant outer tube conforms to the wound canal, the lumen can be enlarged without encountering the leakage problems in Fig. 1.12b[12]

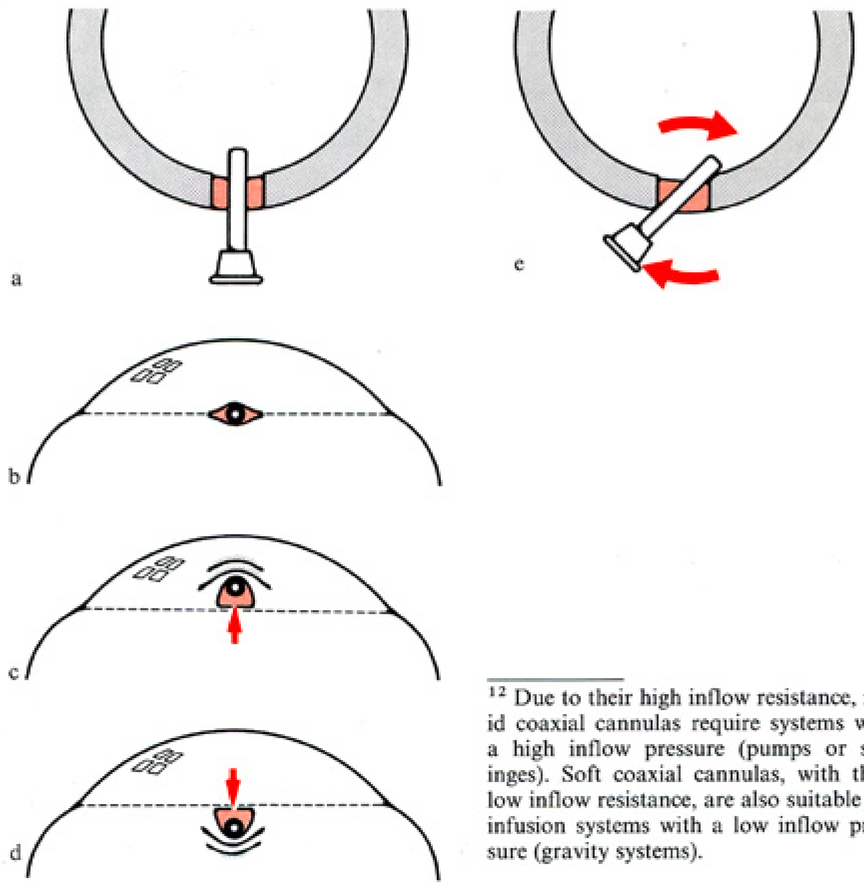

Fig. 1.14. **Effect of cannula placement on wound leak**

Left: Perpendicular movements of the cannula.

a Overhead view.

b Cross-section: When the cannula is precisely on the wound plane, the degree of leak depends only on its external shape (as in Fig. 1.12b, c).

c, d Vertical movements of the cannula increase the leak, and outflow resistance falls. Elevating the cannula (**c**) creates a fold in the chamber wall above the opening. The fold is visible when viewed from above. Lowering the cannula (**d**) makes a fold below the opening, and the surgeon is less likely to perceive the danger of increased leak adjacent to the cannula.

Right: Horizontal movements of the cannula.

e Slewing movements of the cannula may occlude the access opening and increase outflow resistance

[12] Due to their high inflow resistance, rigid coaxial cannulas require systems with a high inflow pressure (pumps or syringes). Soft coaxial cannulas, with their low inflow resistance, are also suitable for infusion systems with a low inflow pressure (gravity systems).

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1.2.2 Viscous and Viscoelastic Materials

Properties

Viscous and viscoelastic materials are characterized by their high internal friction. While flow resistance in watery fluids is determined chiefly by the wall characteristics of the perfused system (Fig. 1.15a), in viscous and viscoelastic materials it is determined largely by the specific rheologic properties of the material itself.

The basic difference between viscous and viscoelastic materials is that *viscous materials* behave like pure fluids and develop internal forces only when their volume is changed; shape changes have no such effect. *Viscoelastic materials*, on the other hand, develop internal forces when their shape and/or volume is changed, so they also have properties of solids.

In **purely viscous materials**[13] the resistance to flow is based on the relationship between the degree of viscosity and the lumen of the per-

[13] Viscosity = shear stress per shear rate.

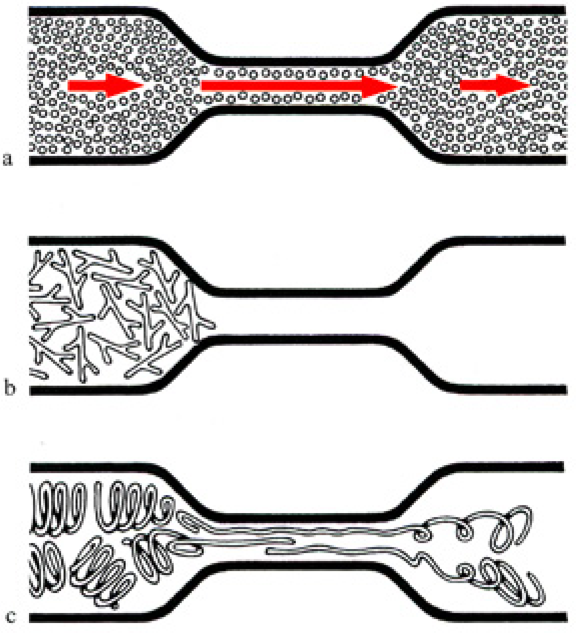

Fig. 1.15. **Behavior of flowing watery, viscous, and viscoelastic substances at constrictions**

a Watery fluids: As the channel narrows, the molecules speed up because equal volumes of fluid must traverse all portions of the channel per unit time.

b Viscous fluid: The relationship of the degree of viscosity to the lumen of the constriction determines whether or not the fluid can negotiate the constriction.

c Viscoelastic materials: The molecular chains deform when passing the constriction, and flow resistance decreases with increasing flow due to molecular rearrangement. Given enough space, the molecules will regain their original form

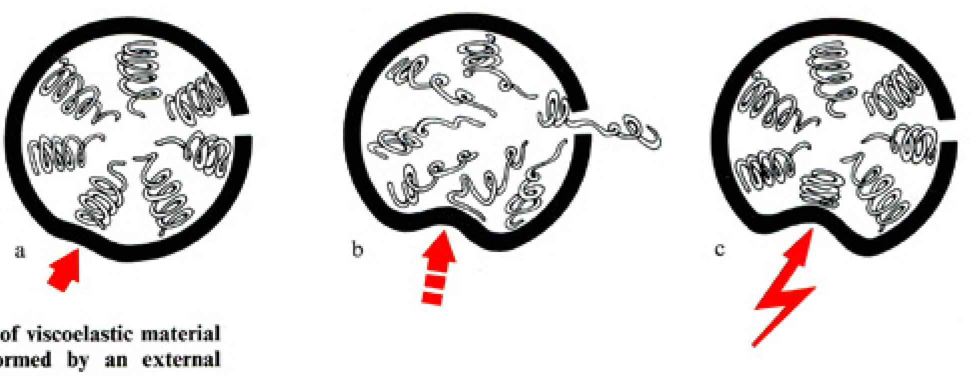

Fig. 1.16. **Behavior of viscoelastic material in a chamber deformed by an external force: significance of the time factor**

a When the force is applied gradually, the material displays viscous properties initially. The outflow resistance, defined by the viscosity and the size of the outlet, determines whether any of the material will be discharged.

b With continued application of the force, the material displays shear thinning as the molecules rearrange and conform to the outlet. This lowers their outflow resistance, and the material flows from the chamber at an increasing rate.

c When a shorter-acting, violent force is applied, the material behaves as an elastic body. The molecules deform without rearranging, and the force is stored locally as elastic energy. No material escapes from the chamber

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fused channel (Fig. 1.15b). Flow properties are more complex in **viscoelastic materials**[14] in that the resistance to flow changes when the material is moved. As a model, we can think of the material as a tangled mass of elastically deformable molecular chains (Fig. 1.15c). The chains are deformed by the action of external forces, and once the forces are removed, the chains can return to their original shape. This process is time-dependent (Fig. 1.16). If the force is applied violently, the molecules pack tightly together and then rebound. If the force is applied more slowly, the molecules have time to rearrange. As a result, viscosity decreases as soon as flow commences, and the material flows more readily ("shear thinning") (Figs. 1.17 and 1.18).

During phases in which the material has *viscous* properties, the mechanical energy of friction is converted to heat. In phases where the material is in an *elastic* state, mechanical effects lead to the storage of elastic energy. It is characteristic of viscoelastic materials that their rheologic properties change continually during use, depending on the speed (change from viscous to elastic behavior) and duration of the impact (change from a high-viscosity to low-viscosity state).[15] The usefulness of a substance for specific surgical goals depends on the shear rate at which the material changes from one state to another.

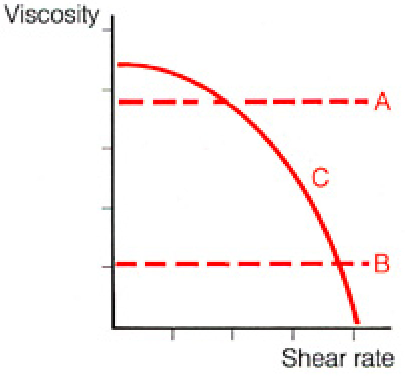


Fig. 1.17. **Viscosity and viscoelasticity**. Dependence of viscosity on shear rate (scale in log log units). Substance *A* has a high viscosity and substance *B* a low viscosity. Both are purely viscous, i.e., their viscosity remains constant with increasing shear rate. But in substance *C*, which is viscoelastic, the viscosity changes with the shear rate. The material is highly viscous at a low shear rate and becomes increasingly fluid as the shear rate increases. This property is called shear thinning ("pseudoplasticity")

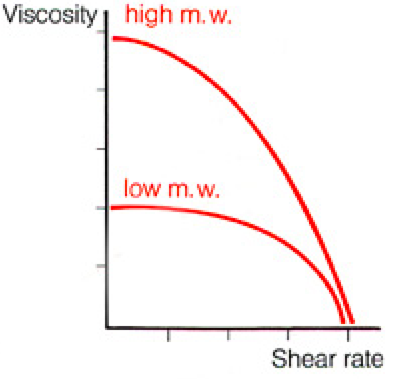
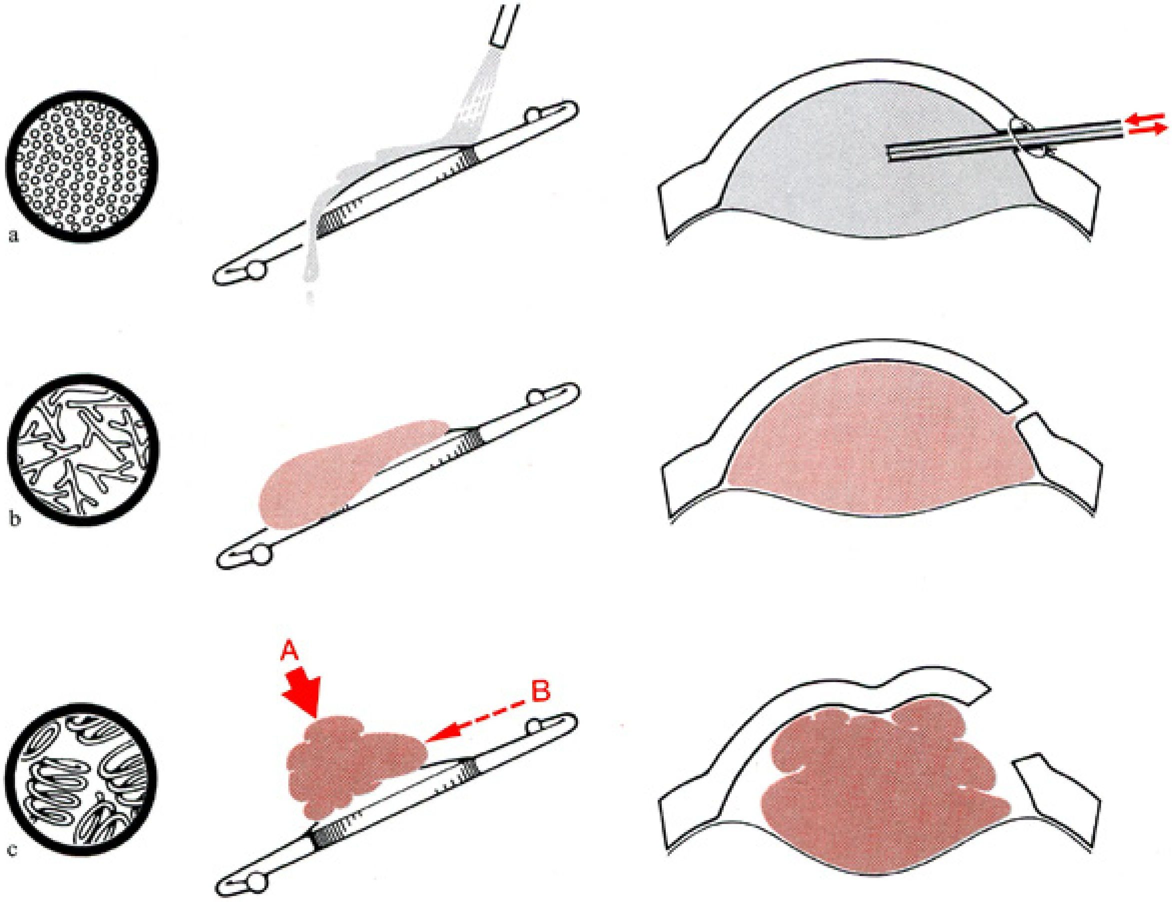


Fig. 1.18. **Dependence of shear thinning on molecular structure and concentration.** Viscosity depends on the volume occupied by the molecules in the flow channel (hydrodynamic volume). Maximum viscosity (i.e. at a low shear rate) is determined chiefly by the shape and length of the molecules (*molecular weight*), i.e., by the hydrodynamic volume of the undeformed molecular mass. Minimum viscosity depends on the *concentration* of the molecules in solution, i.e., on the number of optimally aligned molecules per cross-section in the flow.

The curves represent two substances of different molecular weights in the same concentration. At a low shear rate, the viscosity of the high-molecular-weight substance is higher; at a high shear rate, both substances display nearly equal viscosities

[14] In a strict sense all fluids from water to gas are "viscoelastic," but the size and ratio of the viscous and elastic components vary greatly. In surgical use the term has come to denote viscous substances whose elastic component is so large that it can be used to achieve specific operative goals.

[15] Therefore viscosity data are of little value as a basis for comparing different viscoelastic products, since the data are valid only for a given testing method.



Criteria for the Selection of Viscous or Viscoelastic Materials

For the ophthalmic surgeon, viscous and viscoelastic materials have applications in surface tactics as well as spatial tactics. If they are to be used to maximum advantage, it is necessary to take their different physical properties into account even though both types of material may closely resemble each other in the resting state.

Viscous fluids are best for applications in **surface tactics**, since they form a thick, uniform protective coating when applied to surfaces (Fig. 1.19b). Viscoelastic materials form "plugs" which retain their shape well but protect only against the action of perpendicular forces (Fig. 1.19c).

In **spatial tactics**, viscous and viscoelastic materials are used to create secondary no-outflow systems. In this application viscous implants behave as fluids which, owing to their high outflow resistance, can pressurize a chamber with larger outflow openings than can pure watery fluids (Fig. 1.19b). Viscoelastic implants behave more as solids and can be used in either of two ways: to occupy a space completely ("visco-occupation") or simply to prevent outflow through orifices ("visco-blockade").

In **visco-blockade** (Fig. 1.20) the material is used simply to occlude and seal chamber outlets.[16] This prevents the drainage of fluid that should remain in the chamber to keep it pressurized. Visco-blockade also serves to prevent the undesired

Fig. 1.19. **Comparison of watery, viscous, and viscoelastic substances.**
Left: Applications in surface tactics.
Right: Applications in spatial tactics.

a Watery fluids: Because of their very low viscosity, watery fluids are always applied in a continuous stream.

b Viscous substances flow evenly onto tissue and implant surfaces to form a stable, uniform protective coating. In spatial tactics, the efficacy of the substance (for a given viscosity) depends on the size of the drainage opening.

c Viscoelastic substances: A plug of viscoelastic material protects *surfaces* from perpendicular forces (*A*) but is easily displaced by shear (*B*). The efficacy of viscoelastic materials in *spatial* tactics depends little on the size of the drainage opening, so they can convert ocular chambers and subcompartments into secondary no-outflow systems that maintain their integrity over a given range of stresses (see Fig. 1.14c)

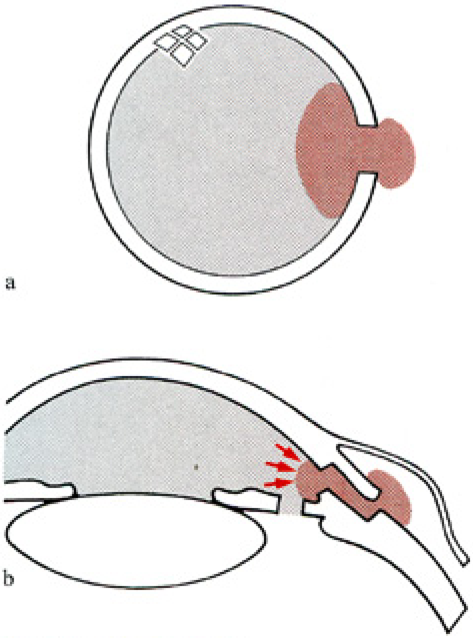


Fig. 1.20. **Visco-blockade**

a Principle: The drainage opening is occluded with a plug of viscoelastic material.

b Sample indication: Aqueous drainage through an antiglaucomatous fistula is blocked with the object of keeping the chamber formed in the early postoperative period. Aqueous circulation in the remaining parts of the chamber is not affected

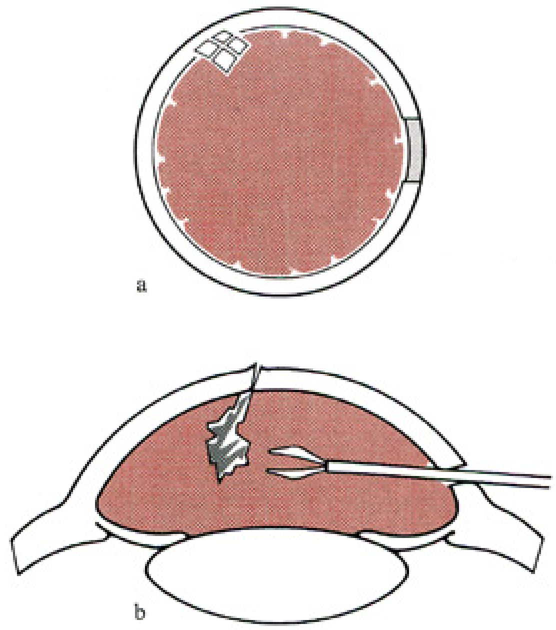


Fig. 1.21. **Visco-occupation**

a Principle: The entire chamber is filled with viscoelastic material.

b Sample indication: During the removal of a sharp-edged foreign body from the posterior corneal surface, visco-occupation protects the endothelium and lens capsule by stabilizing the chamber. Additionally, the material slows the movement of objects, making it easier to control the foreign body during the extraction

influx of extraneous material (blood, lens cortex, vitreous) into certain compartments of the eye.

In **visco-occupation** (Fig. 1.21) the size of the chamber outlet has virtually no effect on the maintenance of pressure, because volume loss is resisted by forces within the viscoelastic material itself (Fig. 1.19c). Hence a space can be stabilized even in the presence of a large outflow opening. This is of particular interest in the subcompartments of the chambers, which cannot be effectively pressurized by any other means.

The stabilization of spaces by visco-occupation differs from stabilization by visco-blockade in the *rheologic situation* that prevails inside the space. Visco-blockade does not alter the environment within the chamber, whereas visco-occupation replaces the physiologic milieu in the chamber with a viscoelastic medium which retards the movement of instruments, implants, and mobile tissues.[17]

Side-Effects

The very properties that are advantageous when applied at the appropriate sites can be disadvantageous at other sites.

Visco-occupation of the wrong compartment in the eye can obliterate the portion of the intraocular volume that would otherwise be needed to expand the target compartment, making it impossible to achieve that expansion. *Visco-blockade* at the wrong sites can

[16] Purely viscous substances are not well suited for this purpose. A substance viscous enough to effectively blockade a wound (that in Poiseuille's formula has a large r and a small L) cannot be injected through a cannula (that has a small r and a large L) unless it is pseudoplastic. Conversely, if a non-pseudoplastic substance can pass through an injection cannula, it could only occlude openings that are even narrower and longer than the cannula.

[17] The damping of movements (visco-tamponade) is an important protection against inadvertent movements of instruments and implants. But visco-tamponade can also have disadvantages such as the prevention of spontaneous iris movements. Further, it allows the transmission of shear forces from instruments with fast-moving parts (e.g., electrically powered trephines, vibrating knifes) to adjacent tissue (e.g., corneal endothelium). Visco-occupation can also prevent the uniform distribution of drugs injected intraoperatively (e.g., acetylcholine, alpha-chymotrypsin), making it necessary to flush the viscoelastic material from the target area before the drug is injected.

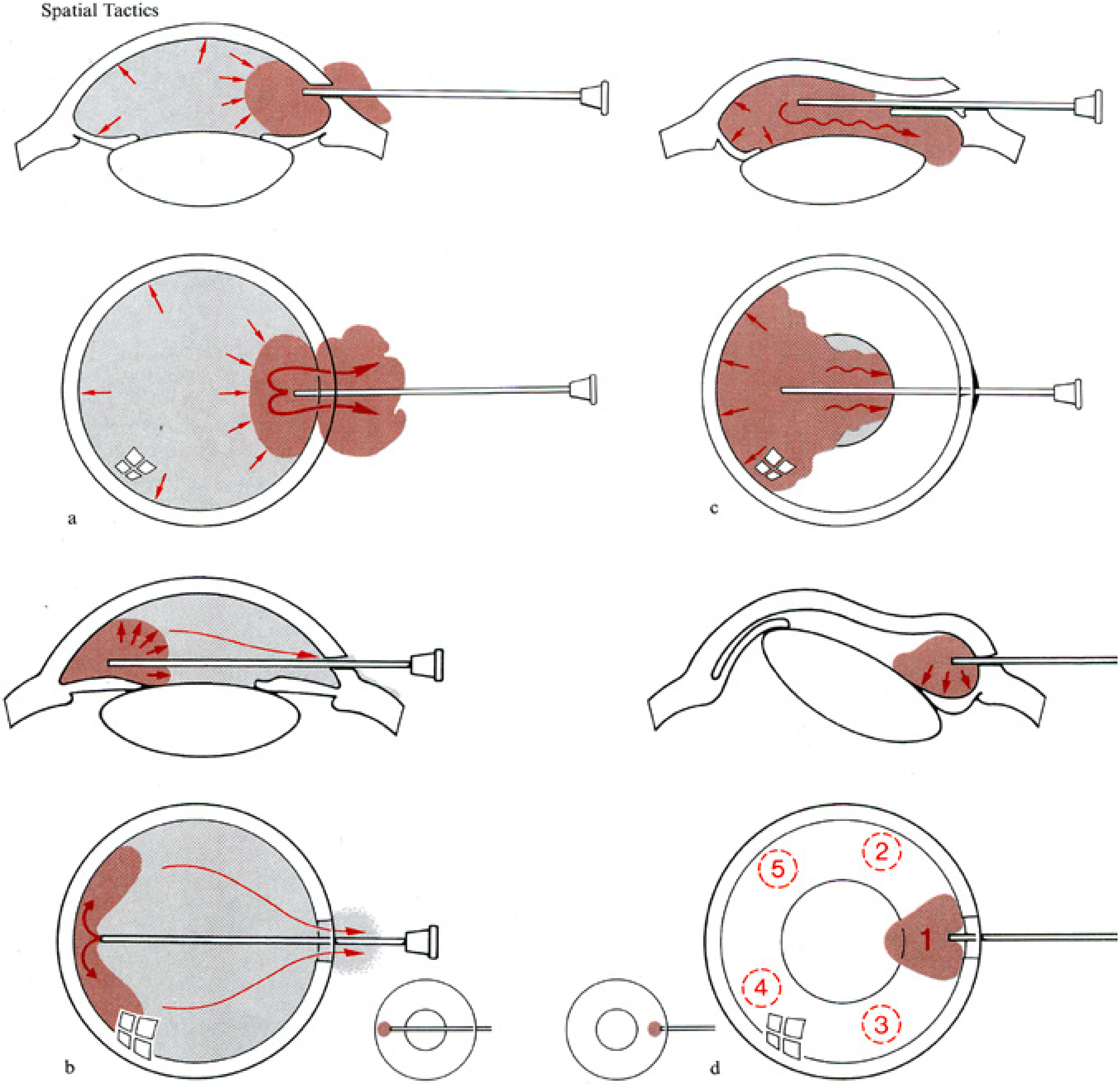


Fig. 1.22. **Application of viscoelastic material: avoidance of side-effects when injecting into the anterior chamber through a small opening**. Comparison of injections into an intact chamber (**a, b**) and a chamber that has been drained (**c, d**).

a, c Injection techniques that lead to side-effects.

b, d Injection techniques that avoid side-effects.

a If injection of the material is started at the access opening, a visco-blockade is formed. This prevents compensatory aqueous discharge, the chamber pressure rises, and the chamber cannot be filled with the material.

b If the injection is started well past the access opening, aqueous can leak, and the anterior chamber can be completely filled with viscoelastic material.

c There is no problem of compensatory aqueous discharge in an evacuated chamber. However, starting the injection opposite the opening may allow some material to get behind the ipsilateral iris. This occurs when the material presses the contralateral iris and lens downward, thus widening the access to the ipsilateral retroiridal space.

d Starting the injection just inside the opening pushes the iris onto the lens and keeps the material from entering the ipsilateral retroiridal space. Additional depots (2 to 5) are then placed about the circumference of the iris until the whole pupillary margin is blocked. At that time the rest of the anterior chamber may be filled.

Note: The two insets emphasize that injection into an aqueous-containing chamber (started opposite the access opening) is exactly opposite to the procedure used for an empty chamber (where injection is started at the opening)

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obliterate passages that should remain clear in the context of the operative goal. This underscores the importance of placing viscoelastic materials *only at the sites where they are needed* and leaving them in place *only as long as they are needed.*

Application

The injection technique differs from that used for watery fluids, because the viscoelastic material must be placed precisely at the target site and nowhere else. In addition, the technique should take into consideration that the injection of viscoelastic implants always produces volume shifts in surrounding compartments. This leads to the following rules for the placement of viscoelastic materials:

- If compensatory volume shifts are desired (Fig. 1.22b), the pathways through which the shifts occur should *not* be obstructed.
- If compensatory shifts are not desired, the corresponding pathways *should* be obstructed (Figs. 1.22d, 1.23b).

Removal of Viscoelastic Materials

The localized removal of viscoelastic material is difficult. Material is most easily removed from a subcompartment if that subcompartment has a compliant, compressible wall (Fig. 1.24).

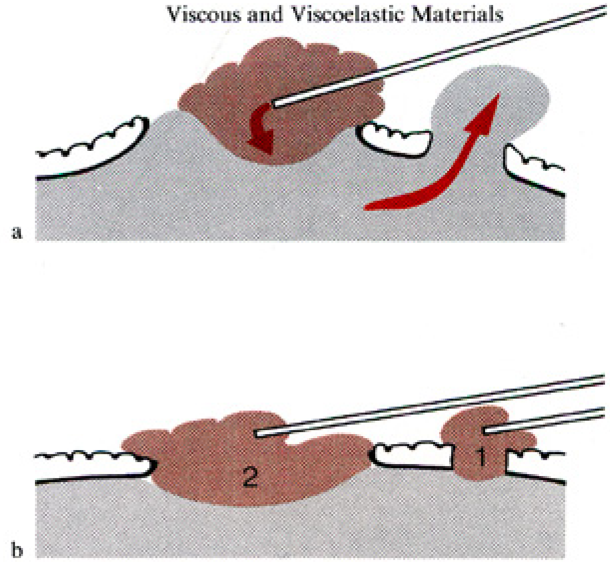

Fig. 1.23. **Application of viscoelastic materials: avoidance of side-effects following intracapsular lens extraction.** Volume shifts inside the chamber.

a Injecting into the pupil first can incite compensatory vitreous prolapse through the peripheral iridectomy. The prolapse, often unrecognized, may be injured by further maneuvers in the anterior chamber.

b This is avoided by occluding the iridectomy with viscoelastic material (*1*) before injecting into the pupil (*2*)

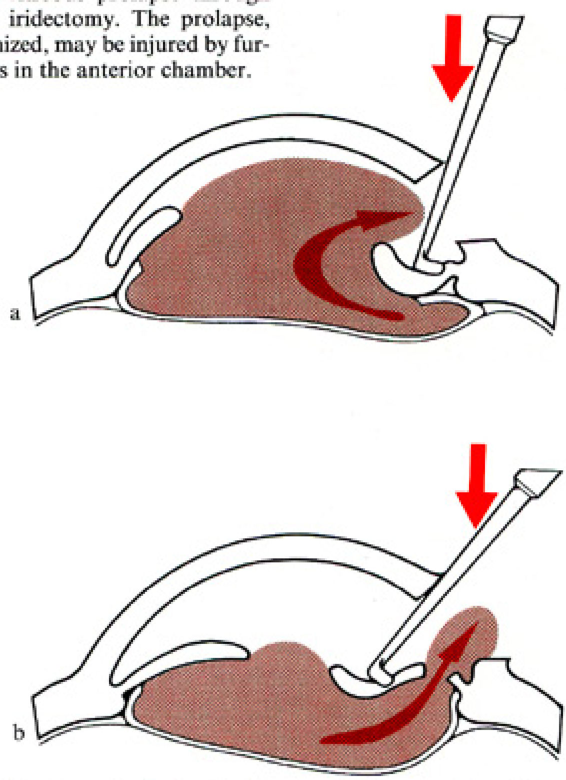

Fig. 1.24. **Selective removal of viscoelastic material from a subcompartment (here: the retroiridal space).** The anterior wall of the space (i.e., the iris) is pressed inward with a broad spatula to expel the viscoelastic material.

Note: Depression of the iris is maintained for a sufficient time to allow expulsion of the slow-flowing material.

a A large pupil provides an adequate outlet for the expulsion.

b If the pupil is small, a second, more favorably positioned outlet is created by iridectomy

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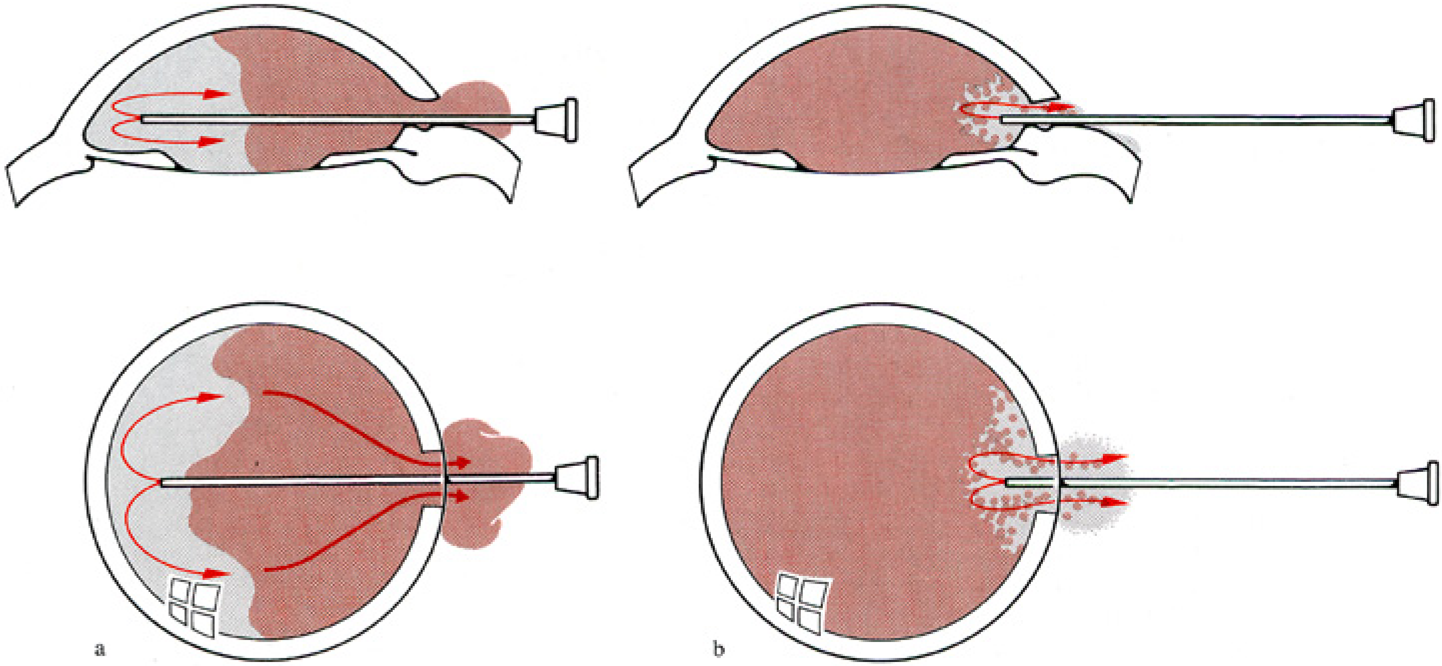

Fig. 1.25. **Evacuation of an entire chamber by irrigation with watery fluid**

a Evacuation in bulk. Watery fluid injected *opposite* to the access opening is kept inside the chamber by the viscoelastic material (visco-blockade). When the intraocular pressure rises sufficiently, the viscoelastic plug is expelled abruptly in one piece.

b Irrigation by dilution. The watery fluid is injected *just inside* the access opening. The material there is diluted and progressively removed with the irrigating stream

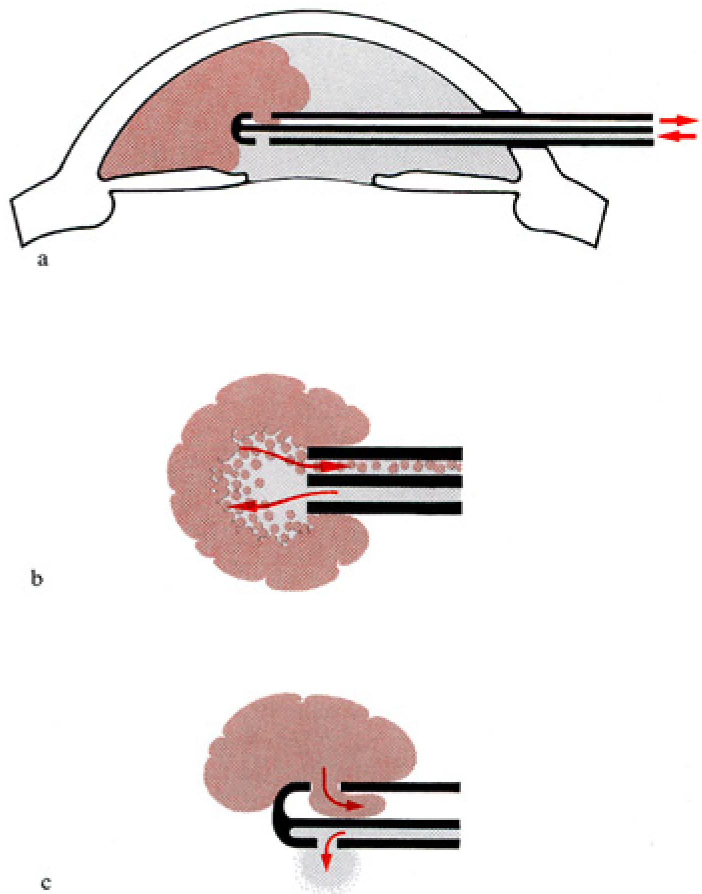

Fig. 1.26. **Evacuation by aspiration** ►

a Use of an infusion-aspiration cannula allows concomitant replacement of the aspirated volume.

b Aspiration of viscoelastic material by dilution. The infusion port should be as close to the aspiration port as possible (i.e., at the tip of the cannula) so that the diluted material is presented directly to the aspiration port.

c Aspiration in bulk. This technique requires an aspiration channel of large caliber due to the high flow resistance of the viscous material. The infusion and aspiration ports should be well separated; otherwise fluid of lower viscosity may be presented to the aspiration port and hinder the aspiration of more viscous material

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Whole chambers can be evacuated by means of *irrigation* (Fig. 1.25) or *aspiration* (Fig. 1.26). In both procedures the material can be removed either *in bulk* (Figs. 1.25a, 1.26c) or by *dilution* (Figs. 1.25b, 1.26b).

In **evacuation in bulk** a large volume of material is extruded at one time. Thus, a sufficiently large inflow capacity is needed to compensate for the sudden volume loss. **Evacuation by dilution** is a more gradual process in which a continuous fluid stream is trained against the material to be evacuated. The pressure in the chamber remains relatively constant, and the chamber volume is easily controlled. On the other hand, the effect is not easily monitored since it becomes increasingly difficult to distinguish the diluted material from the watery ambient fluid as the evacuation proceeds.

The slowest way to evacuate by dilution is to leave the material in the eye. Over time the material will be gradually diluted by aqueous and removed from the eye by natural mechanisms. This option is acceptable when there is reason to continue the effect of the viscoelastic material into the postoperative period.[18]

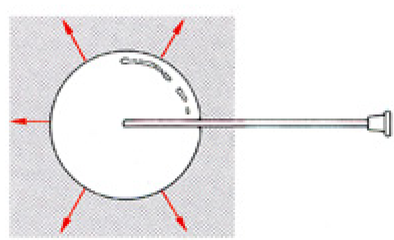
1.2.3 "Membranous" Implants (Bubbles)

When substances that are impermeable to watery fluids are injected into the eye, they form bubbles whose surface behaves like a membrane with respect to its watery environment.

Properties

Bubbles are essentially artificial pressure chambers. They are maintained by the **surface tension** produced by forces of attraction among the molecules in the adjacent media (Fig. 1.27). For a given composition of the bubble and the ambient medium, the surface tension of the bubble is inversely proportional to its size. Small bubbles have a higher tension than larger bubbles, and smaller coalesce with larger on contact (Fig. 1.34c). The largest "bubble" is the atmosphere, and when intraocular gas bubbles come in contact with the open air, they collapse.

[18] Should evacuation of the material become necessary later (the main indication being a postoperative rise of intraocular pressure caused by visco-blockade of natural pathways for aqueous drainage), it can be released through a small keratotomy. Small, valve-like keratotomies are opened by depressing the lower wound margin (see Figs. 1.14c and 5.22b). The pressurized aqueous will expel the residual viscoelastic plug through the incision, whereupon the valve will close spontaneously.



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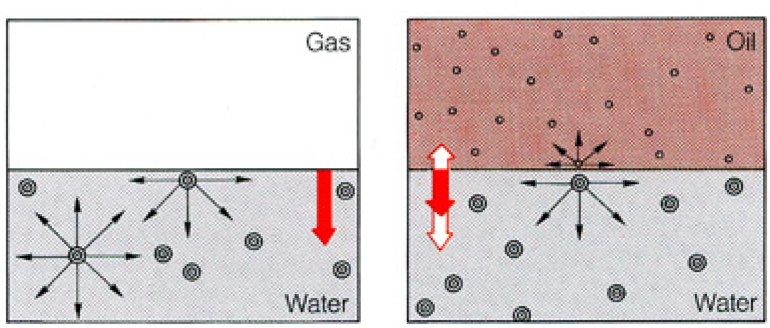

b

Fig. 1.27. **Development of surface tension at interfaces**

a At a water/gas interface, the forces of attraction among the water molecules cancel out within the water-filled volume. No such forces exist on the gas side of the interface, so the water molecules closest to the surface experience a net inward pull.

b At a water/oil interface, molecular attractions in the water are opposed by the (weaker) molecular attractions in the oil. Surface tension is the result of opposing force vectors. It is weaker at the water/oil interface than at the water/gas interface

To intraoperative spatial tactics mainly the surface properties of bubbles are relevant. Their contents are significant only in the way of determining the specific gravity of the bubble.[19]

The surface tension gives bubbles their *spherical shape*. Their tendency to retain that shape under the action of outside forces depends on the level of the surface tension.

Once in place within the eye, bubbles move and transmit forces without direct intervention by the surgeon. They do this under the action of *gravity*, whose effect is based on the difference between the specific gravities of the bubble contents and the medium.

Gravitational forces are opposed by friction, which is higher in bubbles injected into viscoelastic material than in a watery milieu. Accordingly, the surgeon can control the behavior of the bubble by appropriate selection of the bubble contents and ambient fluid. He can control the *direction* of bubble motion by using a light or heavy material,[20] and he can control the *speed* of its motion by providing a watery or viscous milieu.

The discussions that follow refer essentially to compressible air bubbles, although the specific conditions for incompressible silicone oil can be inferred from them.

The **size of the bubble** formed by injecting a given volume of air depends on the ambient pressure. Because air is compressible, a high ambient pressure in the chamber will result in smaller bubbles, and the volume of the bubble will change with the pressure in the chamber.[21] The maximum attainable size in any given situation is determined ultimately by the level of intraocular pressure that can be tolerated.

Indications for Bubbles

Bubbles, like viscoelastic materials, have two basic applications in spatial tactics: *outflow blockade* and *space occupation*.

For **outflow blockade**, bubbles produce an occlusive *seal* of leaks by virtue of their impermeability. The integrity of the seal depends on keeping the eye positioned so that the site to be occluded is uppermost (Fig. 1.28). Further the bubble must maintain sufficient contact with the margins of the opening that is to be occluded. The larger the bubble, the easier the blockade.

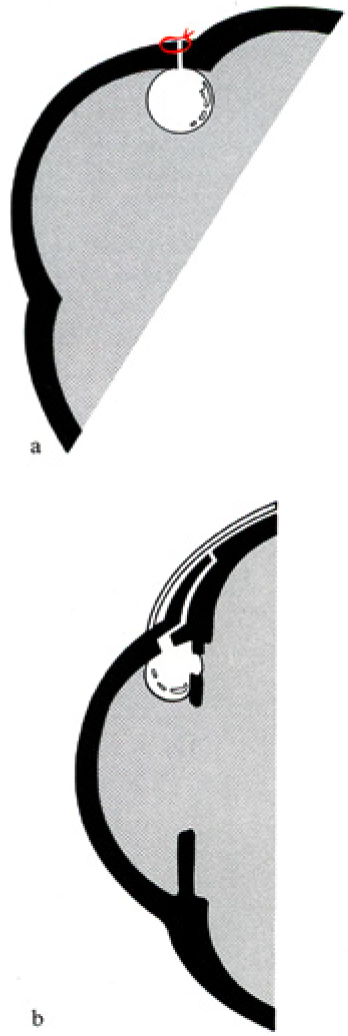

Fig. 1.28. **Outflow blockade with bubbles**

a Principle: The outlet is placed in a position where it will be occluded by the bubble, and it is maintained in that position.

b Example: Temporary blockade of aqueous drainage through an antiglaucomatous fistula, analogous to the situation in Fig. 1.20b. In contrast to a viscoelastic blockade, the effect depends on how well the necessary upright position can be maintained

[19] On the other hand the chemical composition of the bubble contents is relevant to *postoperative* goals, for it determines the duration of placement (absorption time) and size progression of the bubble in the postoperative period. Gases that are soluble in blood are rapidly absorbed. Bubbles composed of exogenous gases (e.g., sulfur hexafluoride, perfluorocarbons) in which the partial pressure of blood gases is lower than in the environment tend to absorb oxygen, nitrogen, and carbon dioxide. Therefore bubbles of this type expand in the early postoperative period, and some time passes before the bubble diminishes in size. By mixing air and gases foreign to the blood in appropriate ways, the surgeon can have some control over postoperative bubble size. Bubbles composed of silicone oil may retain their original size indefinitely, though with passage of time they may become emulsified by the "stirring" action of tissue irregularities in the occupied compartment (e.g., vitreous strands).

[20] Gases and light silicone oil are lighter than aqueous, heavy silicone oils are heavier.

[21] Paradoxically, a bubble may become smaller as additional air is injected (thereby raising the chamber pressure). If a bubble is injected into a chamber that is under high pressure, it will enlarge postoperatively as the intraocular pressure falls due to natural aqueous drainage. This expansile effect is countered by the opposite and simultaneous effect of bubble absorption. It should be noted that the enlargement in this case is not due to the uptake of blood gases but relates to a fall of intraocular pressure.

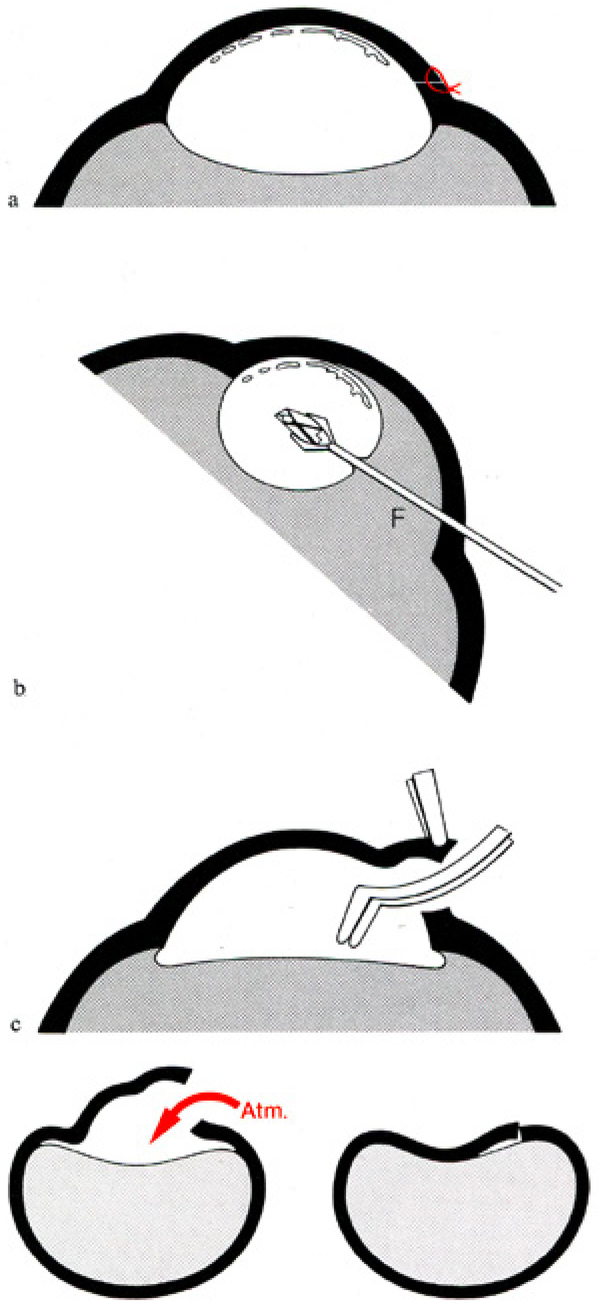

Fig. 1.29. **Space occupation with a bubble**

a A bubble completely filling a large compartment keeps the space free of tissue parts and fluids. If the surgeon now attempts to pass an instrument into the chamber, open air may come in contact with the bubble surface, causing the bubble to burst and collapse.

b When used to aid the removal of a foreign body from the anterior chamber, the air bubble must be positioned so that it is isolated from the incision by a fluid layer (F).[23] If the layer is a watery fluid, instruments designed for use in no-outflow systems should be used because of the low outflow resistance. If the layer is a viscoelastic material, bulkier instruments may be used.

c Air entering the anterior chamber through an open incision does not form a pressure chamber and is simply an extension of the outside environment. The presence of this air indicates that the vitreous pressure does not exceed atmospheric. As there is no danger that air will be expelled, manipulations may be performed freely.
Inset: When the anterior chamber pressure equals atmospheric, the presence or absence of a formed chamber depends not on relative pressures but on the intrinsic stiffness of the cornea. The situations on the left and right are identical in terms of pressure

For **space occupation**, bubbles can be used to occupy and *seal off spaces* that lack natural barriers against the influx of extraneous tissues and fluids (Fig. 1.29a).[22] The ambient pressure will determine whether manipulations can be performed within the occupied space. If the vitreous pressure does not exceed atmospheric, the surgeon can work in the occupied space while the incision is held open. In this case the air in the eye communicates with the air outside, which occupies the portion of the chamber that was previously evacuated (Fig. 1.29c). However, if the vitreous pressure does exceed atmospheric, the bubble must remain pressurized. Its integrity as a pressure chamber can be maintained during manipulations only if instruments are passed into it in a way that keeps it separate from the outside air. This is done by keeping the bubble surrounded by an adequate fluid layer. The outflow resistance of this fluid then limits the pressure at which the bubble can still be maintained.

[22] *Example:* When the anterior hyaloid has been destroyed, an air bubble can be injected to define a space that is entirely devoid of vitreous. The bubble surface acts as an artificial hyaloid, enabling the surgeon to develop an effective counterpressure in the anterior chamber to the vitreous cavity.

[23] In contrast to viscoelastic materials (Fig. 1.21), air is suitable for space occupation only if the globe can be appropriately rotated.

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Side-Effects of Bubbles

During operations the major problem with bubbles is their poor reliability as spatial stabilizers. If manipulations bring their surface into contact with the open air, they rupture. In this case their surface tension and extremely low outflow resistance allow a large volume to escape the chamber so rapidly that collapse is inevitable; the lost air cannot be replaced with an equal fluid volume at the same speed. Consequently, bubbles provide reliable space-tactical instruments only in situations where they can be kept isolated from the environment by *suitable positioning* (Fig. 1.29b).

Postoperatively, bubbles may obstruct paths that should remain open for aqueous drainage, causing a rise of intraocular pressure. This problem is avoided by *repositioning the globe* (or the patient) as required (Figs. 1.30 and 1.31). If the necessary position cannot be maintained around the clock, *additional drainage openings* can be created to provide for adequate aqueous flow drainage (Fig. 1.32).

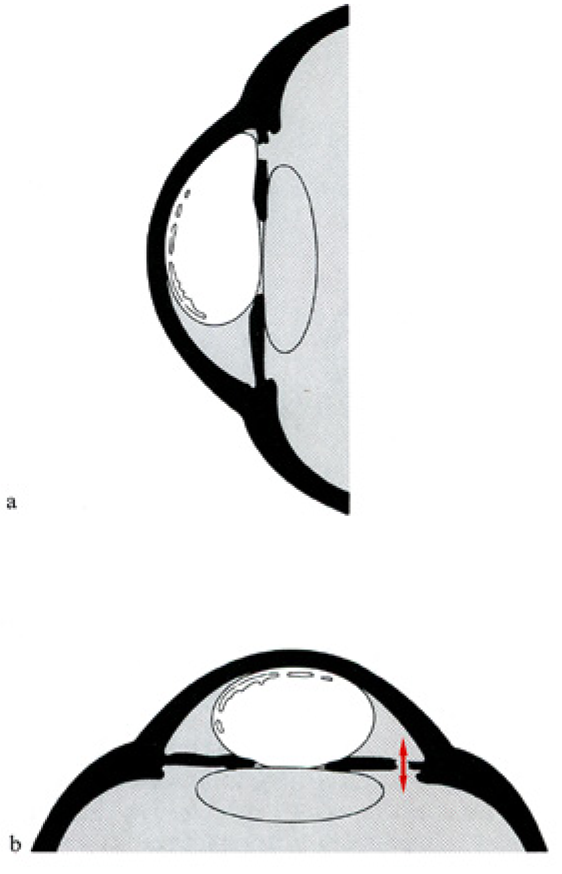

Fig. 1.30. **Obstruction of aqueous circulation by an air bubble**

a With the patient in an upright position, the bubble occludes the superior basal iridectomy. The possibility of aqueous circulation through the pupil depends on the pupil size.

b If the pupil is too small, the basal iridectomy can be uncovered by moving the patient to a supine position

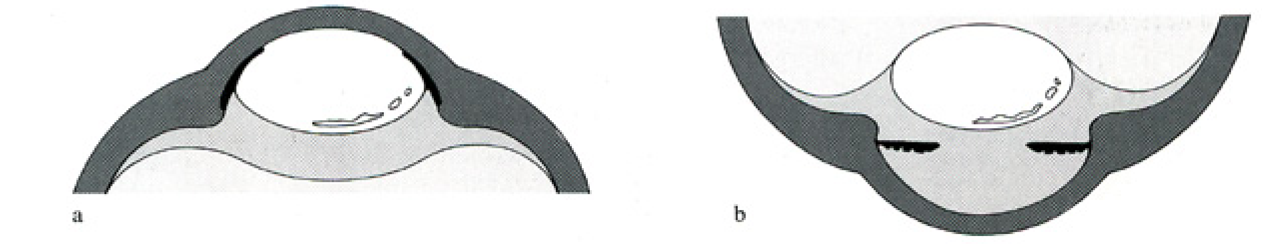

Fig. 1.31. **Obstruction of aqueous circulation in the aphakic eye by an air bubble in the wrong compartment**

a Air trapped behind the iris in an aphakic eye blocks the pupil and obliterates the anterior chamber.

b Moving the patient to the prone position removes the bubble from the iris and restores circulation through the pupil

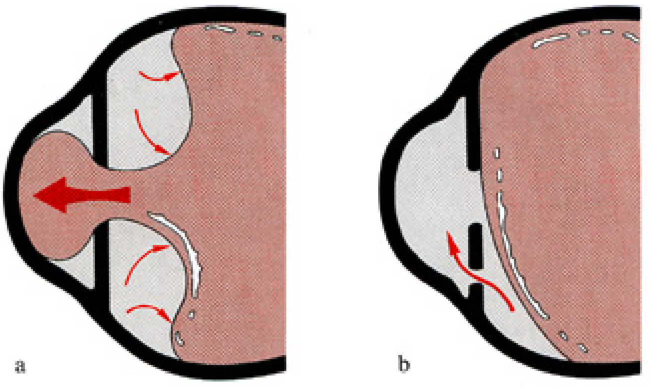

Fig. 1.32. **Obstruction of aqueous circulation in the aphakic, vitrectomized eye: vitreous replacement with silicone oil**

a A silicone bubble can obstruct the pupil in the aphakic eye. Aqueous collects behind the iris, forcing the silicone oil through the pupil towards the cornea.

b Aqueous circulation is restored by iridectomy. The silicone bubble returns to a spherical shape and remains behind the pupil. The iridectomy is placed inferiorly for light silicone oil and superiorly for heavy oil

Application of Bubbles

The technique of bubble injection into the eye affects the size of the bubble but does not determine its **site of action**. The latter depends on the migratory tendency of the bubble, i.e., on the position of the globe (Fig. 1.33) and on the pattern of flow resistances inside the chamber (Fig. 1.34). Accordingly, the site of action of bubbles can be influenced by repositioning the eye and eliminating resistances.[24]

The **size** of bubbles can be controlled by the application technique, at least within the limits imposed by the intraocular pressure.[25] The *choice of the injection site* affects the attainable size in the sense that the bubble may collapse if it can reach the atmosphere at the access opening (Fig. 1.33). The location of the access opening has no effect on bubble size only if the opening is completely sealed around the injection cannula (see Fig. 1.12a), or if the pressure in the chamber does not exceed atmospheric (see Fig. 1.29c).

The *injection technique* influences bubble size in that air injected forcibly is likely to form multiple small bubbles instead of a single large one (Fig. 1.35a). A *large bubble* is formed by advancing the cannula to the center of the emerging bubble and then inflating it gradually by slow, steady pressure on the plunger (Fig. 1.35b, c). Thus, in contrast to the injection of watery fluids, where the cannula remains near the access opening, an air-injecting cannula should be inserted well into the chamber. The tip should be placed initially at a site where sufficient space is available for the desired bubble size (this does not coincide with the site of action!) and then advanced into the bubble itself.

[24] Besides the problems shown in Fig. 1.34 associated with the presence of viscoelastic material in a watery milieu, nonhomogeneities can result from the entry of vitreous into the anterior chamber. This can lead to the undesired spread of air bubbles into the vitreous cavity.

[25] If the bubble cannot attain a sufficient size at the tolerable intraocular pressure, the only recourse is first to lower the pressure by the drainage of chamber fluid.

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Fig. 1.33. **Injection of bubbles into a watery milieu** ►

a If injection is attempted from a high point, the air is in contact with the atmosphere initially, and a bubble cannot be formed – unless the chamber pressure does not exceed atmospheric.

b A bubble injected from a low point will rise from there to the highest point. Air can be injected until the bubble reaches the access site, i.e., downward expansion of the bubble is limited by the position of the access opening

Fig. 1.34. **Injection of bubbles into a nonhomogeneous milieu (irregular distribution of watery and viscoelastic material)**

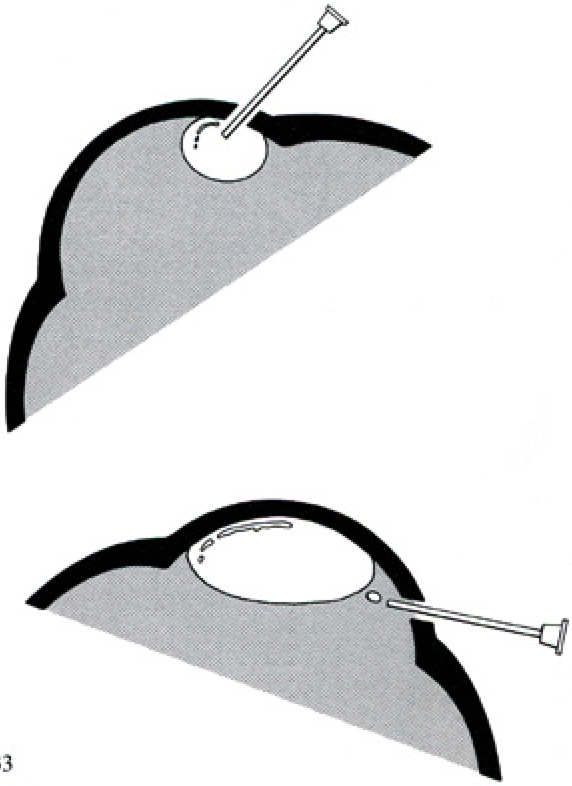
a Air bubbles injected into a nonhomogeneous milieu follow paths of least resistance. Passing along watery "tracks," they may become trapped behind the iris or behind an implant.

b Preparation of a homogeneous milieu in the target area (here, below the corneal apex). Undesired spread is prevented by injecting watery fluid into the target area to create a localized homogeneous milieu.

c Air is then injected into the homogenized area

a

b



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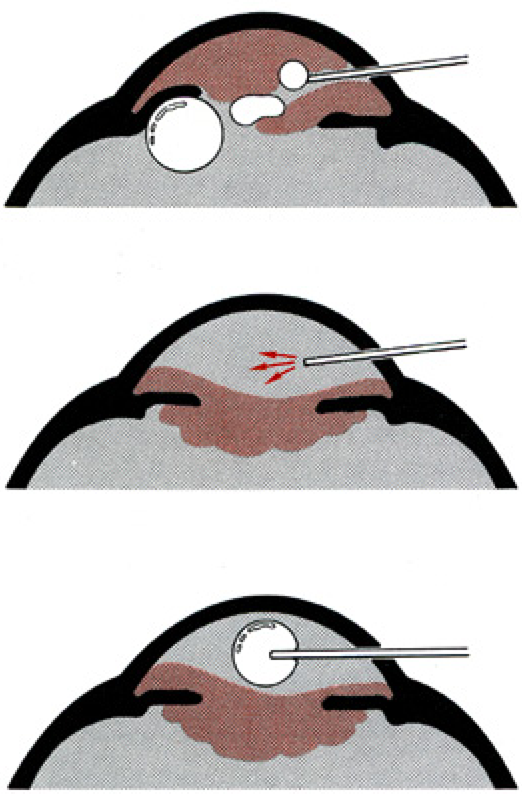

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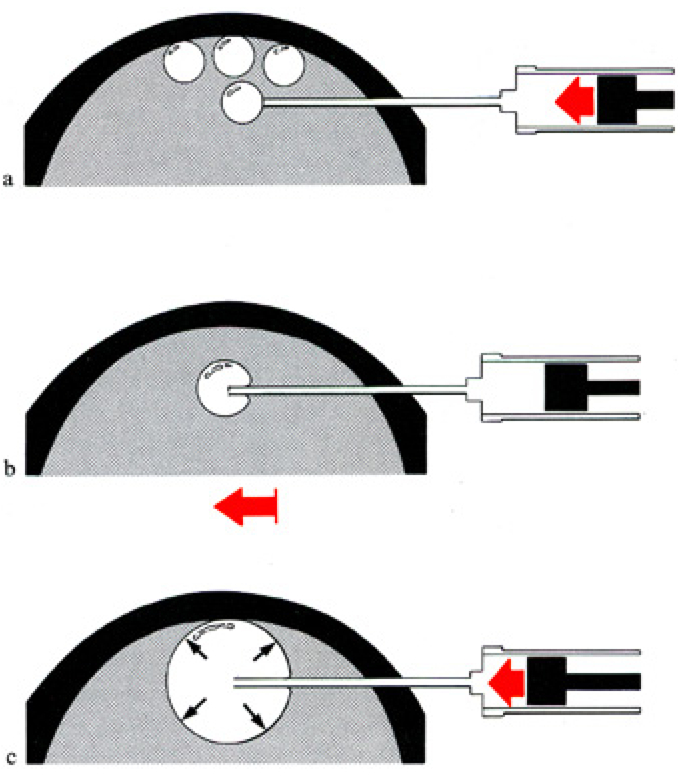

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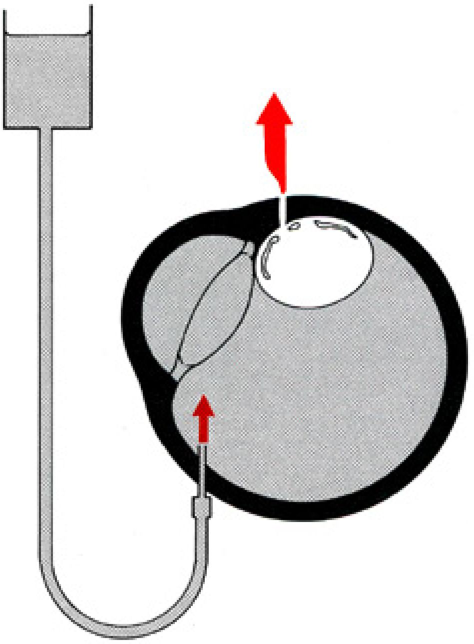
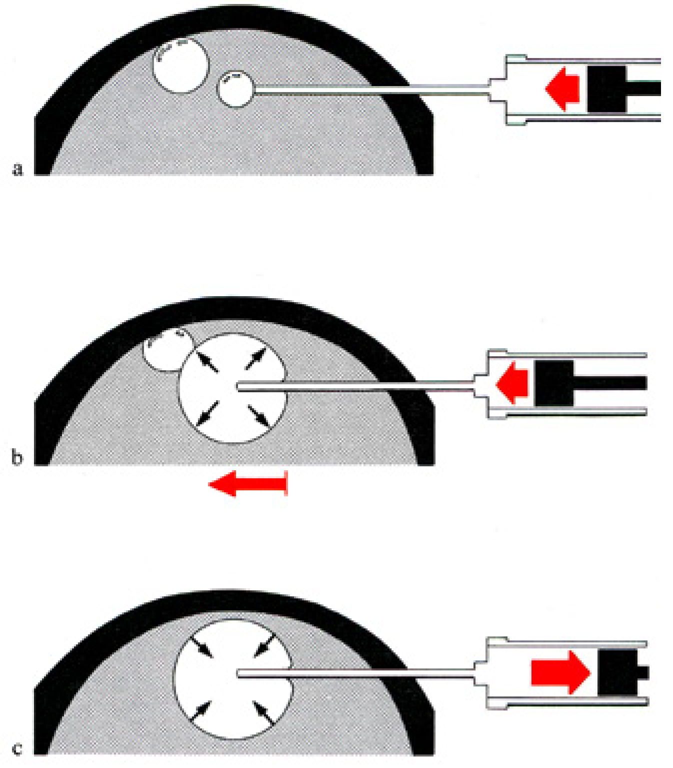


Fig. 1.36. **Removal of bubbles: using buoyancy to expel a light silicone oil bubble.** The globe is rotated until the outlet is uppermost. Fluid is infused at another site to replace the lost volume and maintain the chamber pressure



1.37

Fig. 1.37. **Aspiration of air bubbles**

a Small air bubbles are "captured" by injecting a second, contiguous bubble. (It is paradoxical that the aspiration of air begins with an injection!)

b The second bubble is enlarged by advancing the cannula tip to its center (see Fig. 1.35c). When the second bubble has attained sufficient size, both bubbles will coalesce.

c Finally the cannula is advanced to the center of the single large bubble. The cannula should be kept at the center of the bubble until the aspiration is completed

← Fig. 1.35. **Technique of air bubble injection**

a If the cannula tip is held stationary while injecting air, the bubble will detach and rise as soon as it has sufficient buoyancy, and multiple small bubbles will form.

b To obtain a single large bubble, the cannula tip must be advanced into the bubble during the injection.

c The bubble will gradually expand as air is injected[26]

Removal of Bubbles

The simplest way of removing bubbles is to position the access opening so that the bubble is expelled by its own **buoyancy** (Fig. 1.36). This method is excellent for silicone oil bubbles, which, because of their viscosity, move slowly and allow ample time for volume replacement with fluid to prevent ocular collapse. Gas bubbles are expelled too rapidly for this type of volume replacement, and the suitability of buoyancy expulsion for gas bubbles depends on whether an abrupt volume loss of that size can be tolerated.

The **needle aspiration** of bubbles can be more accurately controlled.[27] If the opening of the cannula is held close to the bubble surface, fluid may be aspirated rather than gas. The cannula should be inserted to the center of the bubble to ensure that its contents are aspirated (Fig. 1.37c). Small bubbles that are displaced by the needle rather than penetrated because of their high surface tension can be engaged by injecting a large adjacent bubble (Fig. 1.37a) and allowing the bubbles to coalesce before aspirating (Fig. 1.37b).

[26] Note: A slow injection rate is essential. Rapid injection may produce multiple small bubbles, especially if the surrounding aqueous contains emulsifying proteins. As stated earlier, small bubbles have a higher surface tension, so they require more energy for their production than large bubbles.

[27] This technique may cause problems with silicone oil bubbles because of their high viscosity (see Fig. 1.15b).

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1.3 The Field of Spatial Tactics

1.3.1 The Pressure Chamber of the Globe

The globe of the eye is a sphere (Fig. 1.38), so any force that deforms the globe will reduce its volume and raise its internal pressure (see Fig. 1.41). Very high pressures may be reached owing to the mechanical strength of the cornea and sclera. In the operated eye, the attainable pressure level depends on the quality of the wound closure.

Because of the very high outflow resistance through natural aqueous drainage pathways, some time is required for an increased pressure to return to its initial level and for any volume loss to occur (see Fig. 1.7). Acute forces do no more than raise the intraocular pressure, while forces of longer duration lead ultimately to deformation of the globe.[28]

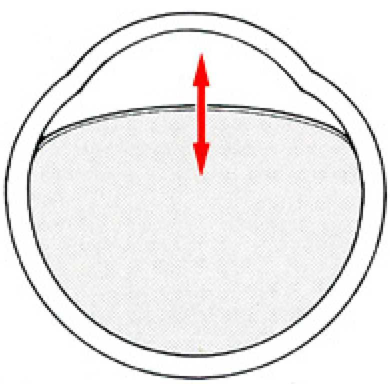

Fig. 1.38. **The pressure chambers of the eye.** The pressure chamber of the overall globe is approximately spherical. The diaphragm subdivides it into two smaller pressure chambers that are nonspherical. Besides anatomic factors, the position of the diaphragm depends on the pressure differential between the two chambers. When the anterior chamber is breached, the vitreous forms the only pressure chamber, and vice versa

1.3.2 The Pressure Chamber of the Vitreous

When the anterior chamber is opened and communicates freely with the outside air (i.e., anterior chamber pressure = atmospheric pressure), the pressure chamber of the vitreous humor remains. This differs from the overall pressure chamber of the globe in its shape and wall strength. Because the vitreous pressure chamber is *not a sphere*, external forces will not necessarily reduce its volume or raise its pressure. The anterior wall of the vitreous chamber, the diaphragm, is thinner and more distensible than the cornea and sclera, and it may be weakened further in the course of operative maneuvers.

The **diaphragm** consists of several membranes arranged in sequential layers (Fig. 1.39). If one of these membranes is perforated during the course of an operation, it is no longer part of the pressure chamber,[29] and the remaining wall is weakened. The innermost layer of the diaphragm is the anterior hyaloid membrane. Once this membrane is breached, the vitreous ceases to form a pressure chamber (Fig. 1.39d).

The distensibility of the diaphragm makes it a useful guide for evaluating the relative pressures in the vitreous chamber and anterior chamber. This forms the basis for the **semiology of the diaphragm**

[28] Permanent deformations like those produced in buckling retinal detachment operations cause a pressure rise immediately after the sutures are tightened, posing a threat to blood circulation in the eye. If decompression by natural drainage is too slow, lower-resistance drainage must be established by surgical means (e.g., puncture of the anterior chamber).

[29] Note: The iris, being perforated by the pupil, does not actually contribute to the anterior wall of the vitreous chamber. However, its opacity makes it an important indicator of the behavior of the transparent membranes of the true diaphragm.

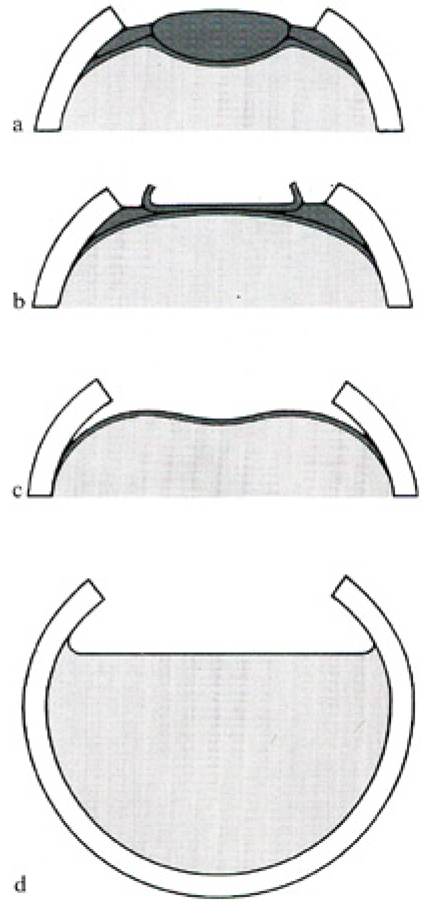

Fig. 1.39. **The vitreous chamber: effects of surgical measures on its anterior wall (the diaphragm)**

a When the anterior chamber is opened, the anterior wall of the vitreous is formed by the lenticulozonular membrane, consisting of the weak, distensible zonule and the rigid, stable lens.

b When the anterior lens capsule is opened, the diaphragm consists of the zonulocapsular membrane, which contains no rigid parts.

c If the zonulocapsular membrane is breached, the vitreous chamber is bounded only by the very delicate anterior hyaloid membrane.

d With rupture of the anterior hyaloid, the vitreous loses its containment and ceases to exist as a pressure chamber

‹ ›

(Fig. 1.40). As long as the diaphragm remains in its **anatomic position**, the pressure in the vitreous chamber equals that in the anterior chamber. Thus, when the anterior chamber is opened, the diaphragm will remain stationary only if the vitreous pressure is zero (i.e., equal to atmospheric). **Anterior movement of the diaphragm** signifies that the vitreous pressure exceeds the pressure in the anterior chamber. The difference may result from negative pressure in the anterior chamber (capillary attraction of the diaphragm to the posterior corneal surface), in which case the pressure in the vitreous may still be low (Fig. 1.40a).[30] But if the difference results from elevated pressure in the vitreous chamber, the surge of the diaphragm is not limited to the anterior chamber, and intraocular contents may even be exteriorized (Fig. 1.40c).

Recession of the diaphragm signifies a fall of pressure in the vitreous space. If not caused by surgical manipulation, a recession of the iris should raise suspicion of a ruptured anterior hyaloid with prolapse of free vitreous into the anterior chamber (Fig. 1.40e).

a

b

c

d

e

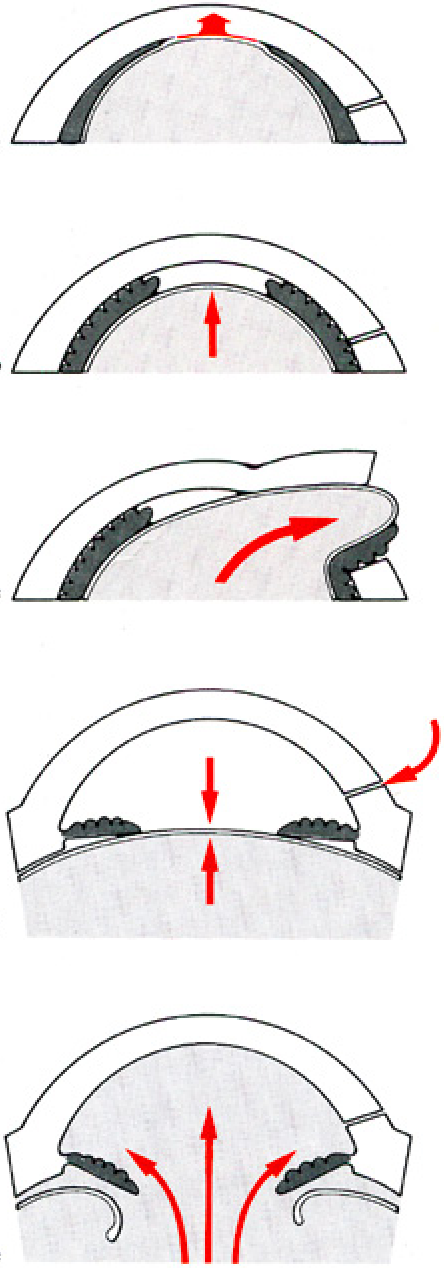

Fig. 1.40. **Semiology of the diaphragm.** Indicators of vitreous pressure with an open anterior chamber.

a "Negative pressure" prevails in the anterior chamber when the diaphragm is pulled forward by capillary attraction. The iris trabeculae are pressed flat against the inner corneal surface, and their normal contour is obliterated.

b With a positive pressure in the vitreous chamber, the anterior chamber discharges most of its contents, but the iris contour is preserved, and some chamber volume is retained at the pupil. Iris flattening as in **a** is very unusual in case of a non watertight chamber, and a further rise in vitreous pressure would most likely produce the situation in **c**.

c Vitreous prolapse: If the vitreous pressure becomes high enough to overcome the elastic resistance of the cornea, the diaphragm will protrude outward through the wound.

d When the anterior chamber is repressurized to a level matching the vitreous pressure (by effective wound closure and fluid infusion), the diaphragm returns to its anatomic position.

e A fall of vitreous pressure is manifested by recession of the diaphragm. This occurs when the pressure chamber of the vitreous is destroyed, and signifies perforation of the anterior hyaloid

1.3.3 Effect of Deforming Forces on the Pressure Chambers of the Eye

Any deformation of the **entire globe** will raise the intraocular pressure (Fig. 1.41). Only the magnitude of the applied forces is significant; the site at which the forces are applied is immaterial. But for the **pressure chamber of the vitreous**, the site of force application is an important factor. Deformations *above* the diaphragm do not affect the vitreous chamber or its pressure. Deformations *at the level* of attachment of the diaphragm reduce its area and relax the membranes, which then may undergo significant displacement or prolapse.[31] Deformations *below* the attachment of the diaphragm do not change its area, and the diaphragm remains tense. The pressure in the chamber can rise and stretch the membranes, possi-

[30] Besides referral to morphologic signs (Fig. 1.40a, b), negative pressure in the anterior chamber can be differentiated from a high vitreous pressure by placing a few drops of watery fluid on the wound margin. With a negative pressure the fluid will be sucked into the wound, and the diaphragm will recede. With a high vitreous pressure this will not occur, and it is necessary to repressurize the anterior chamber by effective wound closure so that its internal pressure can again be increased to the level of the vitreous pressure (Fig. 1.40d).

[31] Iris prolapse is based on different mechanisms, since the iris is not part of the diaphragm (see footnote [29], p. 28). A prolapsing iris first flattens against the wall of the globe, for a time acting as a valve and restoring the pressure chamber. A further pressure rise will cause the iris (the least stable part of the wall) to bulge and protrude through the corneal opening (see also Fig. 7.3c). Iris prolapse thus depends on the pressure in the entire globe, not just in the vitreous chamber, and can be produced even by deformations above the diaphragm.

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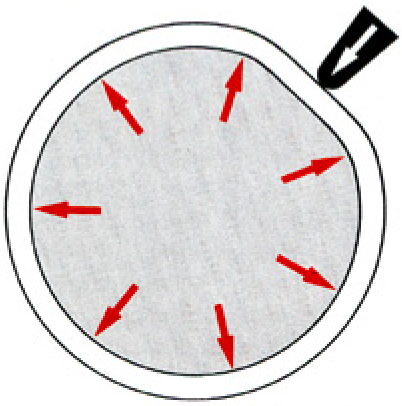

Fig. 1.41. **Deformation of the globe**. A sphere has the smallest possible ratio of surface area to volume. Any change in its shape will reduce the volume. No matter where the deforming forces are applied, the effect is the same (Pascal's law)

bly to the point of prolapse or even rupture (Fig. 1.42).[32]

Even in the **breached vitreous chamber**, the effects of a deforming force depend on its site of application. Since the pressure in the vitreous can no longer rise, the only effect of applied forces is to deform the vitreous body. For a given volume displacement, the rise in the fluid level is greatest when the deforming force is applied at the level of the vitreous face, thereby reducing its surface area (Fig. 1.43).

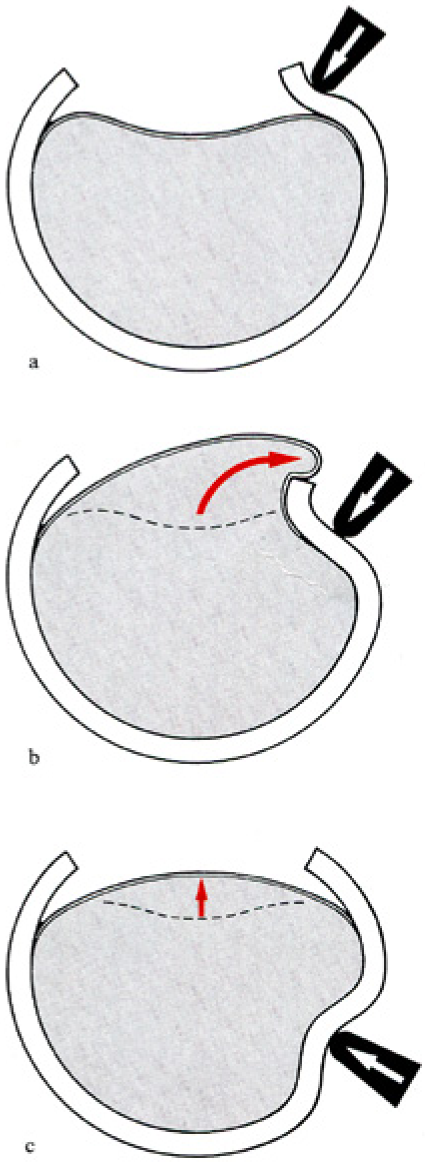

Fig. 1.42. **Deformations of the vitreous chamber**. The effect of deforming forces on the vitreous body depends on the site of application.

a Deformation of the globe anterior to the diaphragm has no effect on the pressure chamber.

b Deformations of the globe at the level of the diaphragm relax the membranes and can cause significant vitreous displacement without raising the vitreous pressure.

c Deformations posterior to the diaphragm tense the membranes and raise the vitreous pressure

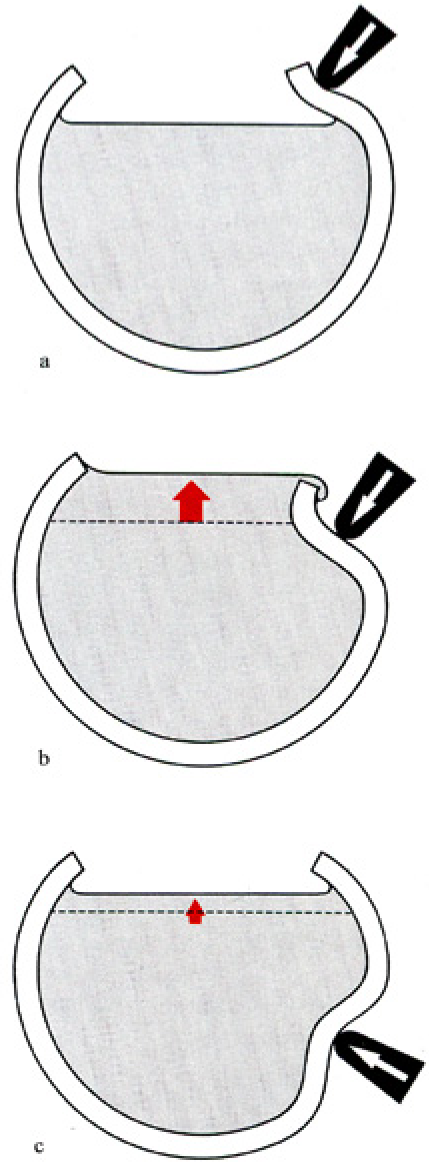

Fig. 1.43. **Deformation effects in the breached pressure chamber of the vitreous**. Here too, the effect of the deforming force depends on the site of the deformation.

a Deformations of the globe above the vitreous face do not affect its level.

b Deformations at the level of the vitreous face reduce its surface area. The fluid face rises markedly in relation to the displaced volume, and prolapse occurs.

c Deformations below the vitreous face do not change its surface area, so the fluid face rises less than in **b**

[32] The two mechanisms of prolapse differ fundamentally. The prolapse of Fig. 1.42b is a purely anatomic displacement caused by geometric factors at low pressure; the membranes may remain intact and are reducible when the cause has been removed. The prolapse mechanism of Fig. 1.42c is caused by increased pressure, is associated with stretching of the membranes, and poses significant risk of membrane rupture.

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1.3.4 Deformations Caused by External Forces

Mechanisms

Every external force acting on the globe has two effects: *displacement* of the globe within the orbit and *deformation* of the globe itself. Which effect is predominant is a matter of resistances. When there is high resistance to ocular displacement, an applied force will tend to deform the globe rather than displace it. Conversely, the globe will undergo little or no deformation if it is mobile enough to be pushed aside by an applied force, i.e., if its passive mobility is high. The **inward mobility** of the globe is determined chiefly by the resistance of the orbital cushion (Fig. 1.44a). Its **outward mobility** is limited by the resistance of the extraocular muscles and of any mechanical barriers such as lid retractors, tense eyelids, etc. (Fig. 1.44b). **Movements of the globe about its center of rotation** meet minimal resistance because the eye and orbit, much like a spheroidal joint, are designed for maximum freedom of rotation (Fig. 1.44c).

External forces will deform the globe only if its passive mobility is restricted.[33] Unrestricted passive mobility, then, offers the best protection against unplanned deformations of the globe. On the other hand, excessive mobility is clearly disadvantageous when it interferes with planned surgical actions. Thus, unrestricted passive mobility is appropriate as a general safety strategy for most of the operation, but for *specific manipulations* it may be necessary to suspend passive mobility by temporary fixation of the globe.

In the immobilized globe, the **direction of application** of the force vectors determines the effect on the ocular pressure chambers. Maximum deformation is produced by *perpendicular* vector components and minimum deformation by *tangential* vector components (components parallel to the ocular surface). Thus, manipulations with perpendicular vectors are appropriate only when deformation of the globe is intended (Fig. 1.45a). Otherwise they should be strictly avoided and replaced with techniques that involve just the application of tangential forces (Fig. 1.45b).

[33] Examples: Passive ocular mobility may be reduced by increased orbital resistance due to infiltration with anesthetic or blood, or by a high muscle tone.

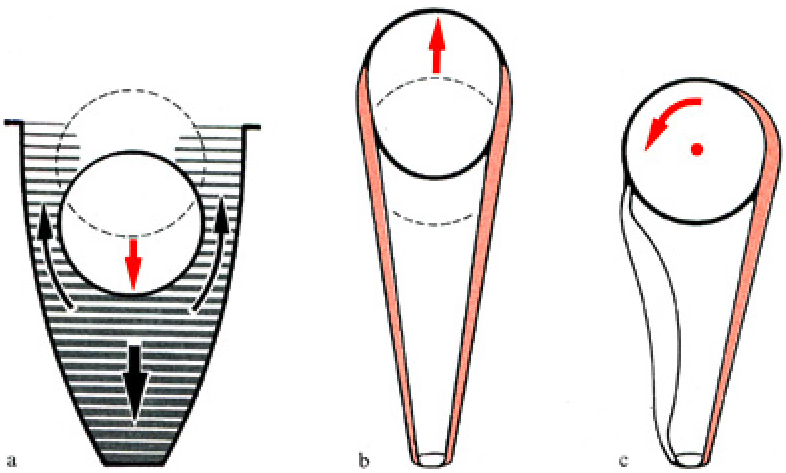

Fig. 1.44. **Factors influencing the passive mobility of the globe**

a The resistance to *inward* movement of the globe depends on the compliance of the orbital cushion.

b Resistance to *outward* movement of the globe depends on the distensibility of the ocular muscles and other adnexa.

c Movements of the globe about its *center of rotation* encounter minimal resistance and actually are limited only in pathologic states (e.g., abnormal muscle tension, adnexal scarring)

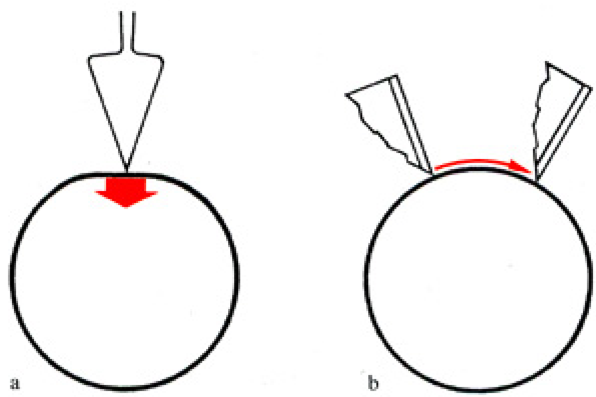

Fig. 1.45. **Effects of deforming forces on the immobilized globe**

a Perpendicular vector components (directed toward the center of the globe) cause maximal deformation of the ocular chambers.

b Tangential vector components (parallel to the ocular surface) cause minimal deformation

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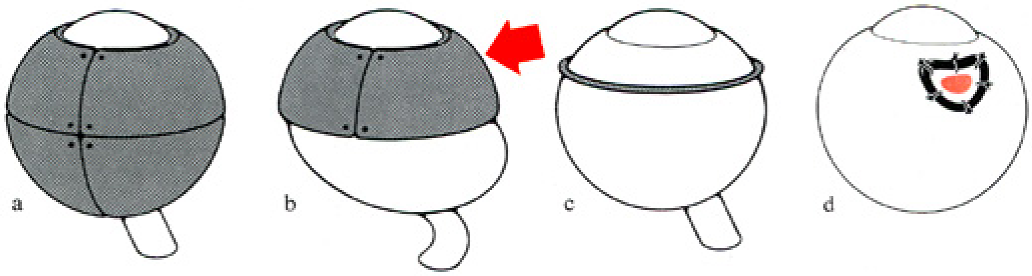


Fig. 1.46. **Stabilization of the chambers by corset systems**

a Total protection can be achieved only by the complete encasement of the eye – obviously an impractical solution.

b Partial corset systems protect against locally applied forces. But if the forces displace the corset as a whole, the corset system itself can be a source of deformation, the effect depending on the width of the system.

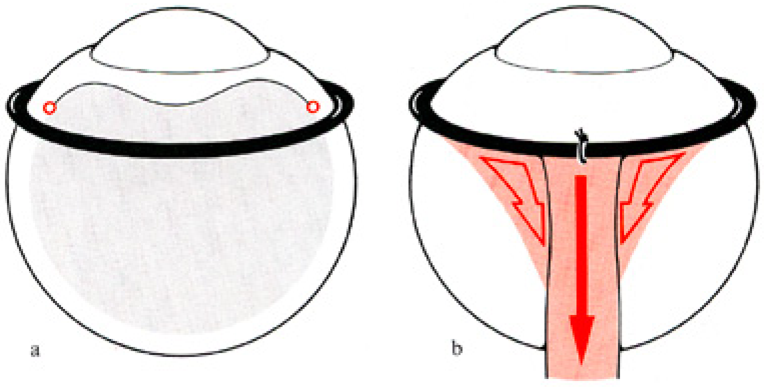
c Maximum reduction of the system width leads to a simple stabilizing ring.

d Specially configured rings for local use protect specific areas from deformation (e.g., the margins of excisions) but do not protect entire chambers. As static fixation instruments, their application lies more in the area of tissue tactics than spatial tactics

Fig. 1.47. **Stabilization of the vitreous chamber**

a A ring fixed to the globe at the level of the diaphragm attachment stabilizes against deformations that cause the greatest shifts of intraocular tissue (see also Figs. 1.42, 1.43).

b If the ring is attached at the insertions of the extraocular muscles, the force of the muscles is distributed over a larger and more stable area, so their deforming action is reduced



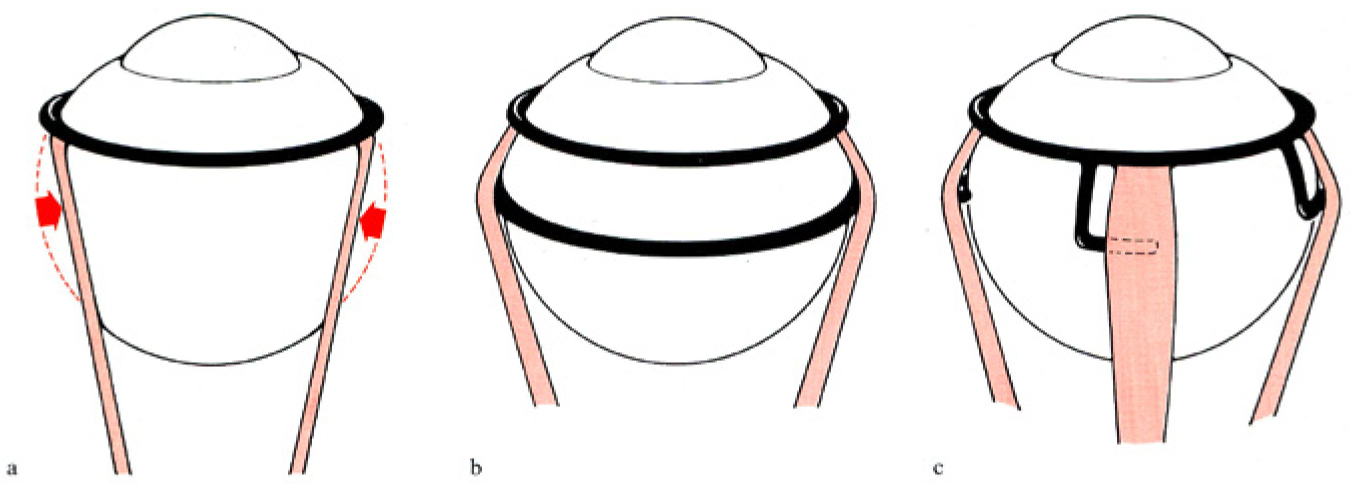


Fig. 1.48. **Protection of the equatorial zone**

a Indentation of the equatorial region by contraction of the extraocular muscles.

b The equator is protected by placement of a second ring.

c In a simpler system having the same effective width (analogous to Fig. 1.46b), the primary ring carries outrigger extensions that slip beneath the muscle insertions

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Protection from External Deforming Forces

External corset systems suitable for practical use are always a *compromise* (Fig. 1.46). In principle, systems with a large contact area would be most effective in protecting the eye from compression[34], but a large contact area is potentially destructive when forces become large enough to displace the entire corset (Fig. 1.46b). Reducing the contact area to a minimum leads to a simple ring configuration.

Stabilizing rings are most effective when they are used to protect the *areas* whose deformation would be most hazardous from the *forces* most likely to cause such deformations. Rings attached at *muscular insertions* accomplish both goals. They reduce the pressure caused by unforeseen muscular tension (Fig. 1.47b) while also stabilizing the area of attachment of the diaphragm, whose deformation is known to cause the greatest clinical problems (Fig. 1.47a).

Of course such rings cannot prevent indentation of the globe by the eye muscles at the equator, where the ocular diameter exceeds the ring diameter. A *second stabilizing ring* would be needed to prevent equatorial compression by muscle tension (Fig. 1.48).[35]

Internal stabilization can be accomplished with viscoelastic materials, which offer resistance to deforming forces by virtue of their elasticity.

[34] Pressure = force per unit surface area.
[35] The risk-to-benefit ratio of a two-ring system is not very favorable, since deformations in the equatorial region produce a relatively minor effect (see Fig. 1.42c) that can be managed with an appropriate margin of deformation (q.v.). Conversely, a two ring system, especially with connected rings, behaves like the partial corset in Fig. 1.46b.

1.3.5 Deformation by Hinge Folds

The mechanism for opening a flap-shaped incision involves *rotation of the flap* about an axis connecting the ends of the incision (Fig. 1.49). This rotation produces a *hinge fold*, which can deform the vitreous chamber (Fig. 1.53).

The formation of a fold on a sphere is associated with complex tissue displacements (Fig. 1.50). The most important of these effects can be characterized as "intramural alignment" and "extramural alignment."

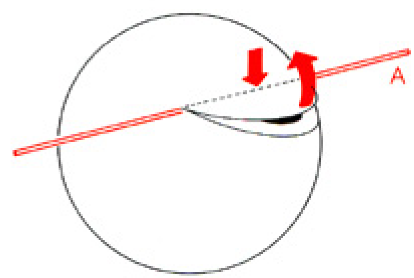

Fig. 1.49. **Formation of a hinge fold.** Any incision that does not follow the path of a great circle produces a flap that can be elevated to open the wound. The flap rotates on an imaginary "hinge axis" (*A*) connecting the ends of the incision. If the flap is turned upward, the domed ocular surface along the hinge axis becomes flattened, and a fold is produced

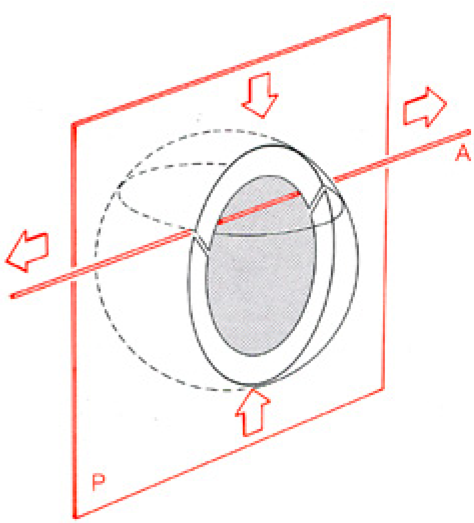

Fig. 1.50. **Analysis of fold formation.** When a flap is raised, the axis of rotation must be straight even though the ocular wall is spherical. To form the axis, all parts of the ocular wall lying above the straight line connecting the ends of the incision must move onto that straight line (the imaginary hinge axis). Any change in the spherical contour of the globe has far-reaching effects. The most important of these effects occur on the vertical plane (*P*) through the axis (ends of the flap-shaped wound). This plane is indicated in subsequent figures, which illustrate the surgically relevant changes in detail

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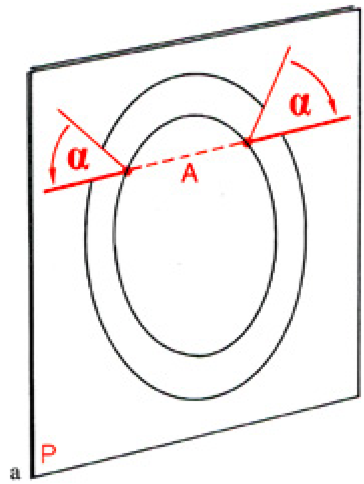
Intramural alignment refers to the *rotation of the wound surfaces* in the direction of the hinge as the flap is raised (Fig. 1.51). This rotation is accompanied by stretching and compression of the tissues encompassed by the incision, setting up a resistance whose magnitude depends on the angle between the wound surface and the hinge line.

Extramural alignment is the *flattening of the ocular dome* that occurs over the hinge axis. This causes the ends of the wound to move apart, the degree of separation depending on the height on the dome above the hinge axis (Fig. 1.52). If this diverging effect is opposed by a high resistance (due, for example, to the stiffening of the tissue during intramural alignment), raising the flap will cause an *inversion of the ocular dome* with a correspondingly greater mass effect upon the vitreous (Fig. 1.52d).

The effects of a hinge fold on vitreous pressure depend on the *position of the hinge fold* relative to the vitreous chamber. With *corneal* folds, the anterior chamber provides a certain spatial reserve, and the position of the hinge axis in relation to the diaphragm will determine whether a danger is posed to the vitreous (Fig. 1.53).[36] *Scleral* flaps always affect the vitreous chamber, and even the slightest infolding will elevate the vitreous pressure.

The problems of hinge folds can be reduced by an appropriate incision technique. Thus, *intramural alignment* is influenced by the *profile* of the incision, which can be modified so that the primary angle between the wound surface and hinge line is zero (Fig. 1.51b, d). *Extramural alignment* is influenced by the *shape of the flap*, which can be tailored to minimize the height of the ocular dome (Figs. 1.54, 1.55).



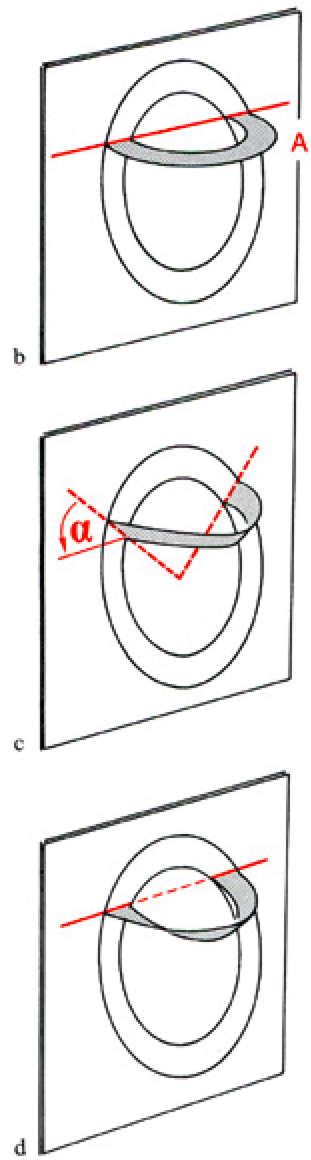


Fig. 1.51. **Intramural alignment**

a The wound surfaces form the angle α with the hinge axis. On elevation of the flap, the wound surfaces rotate through this angle as they align onto the plane of the hinge axis.

b If the wound surfaces lie initially on one plane, α is zero. The surfaces are not twisted as the flap is raised, and there is minimal resistance to hinge formation.[37]

c In other types of incision α is greater than zero.[38]

d When these incisions are opened as flaps, the ends of the wound twist until they are on a straight line. Resistance to this torsion is eliminated by giving the wound surfaces the shape that would result from the twisting action, i.e., by cutting the ends so that they lie on the hinge axis primarily (see Fig. 5.55c)

[36] With a shallow anterior chamber, raising a flap causes an immediate rise of vitreous pressure. Even the initial attempt to raise the flap may incite vitreous prolapse.
[37] For example: keratome and cataract knife incisions have surfaces that lie *primarily* on the hinge line (see p. 164–168).
[38] Arbitrary angles can be made when cutting with scissors.

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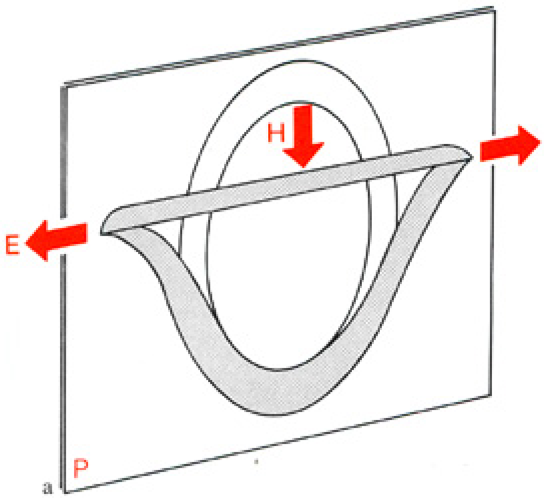

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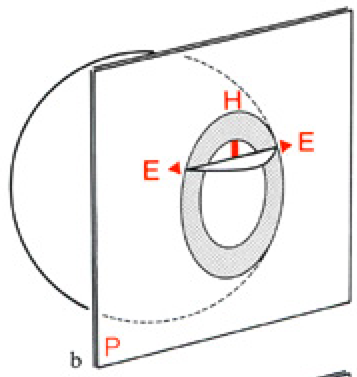

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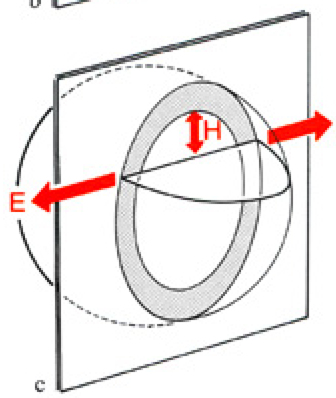

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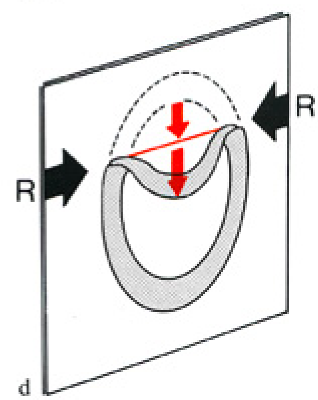

d

Fig. 1.52. **Extramural alignment**

a Because an arc is longer than its tendon, the lateral ends of the wound must separate as the domed wall flattens. The extent of this separation (*E*) depends on the height of the dome (*H*) above the hinge axis.

b *H* is small in short flap incisions, so lateral separation is slight.

c *H* is large in long incisions, so there is greater lateral divergence of the wound ends.

d If this divergence is opposed by a high resistance (*R*), the dome will bow inward, and hinge formation will have a greater compressive effect on the vitreous chamber

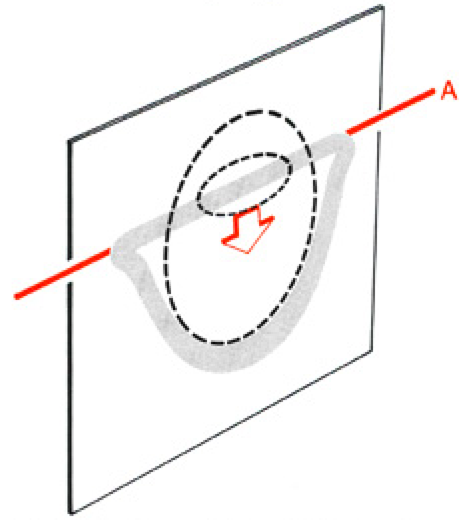

Fig. 1.53. **Effects of hinge-fold formation on the vitreous chamber.** If the diaphragm is above the imaginary hinge axis, it will be pressed downward as the hinge forms, and the vitreous pressure will rise

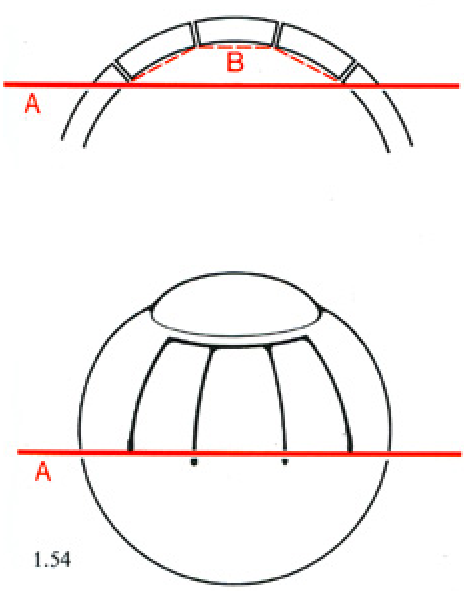

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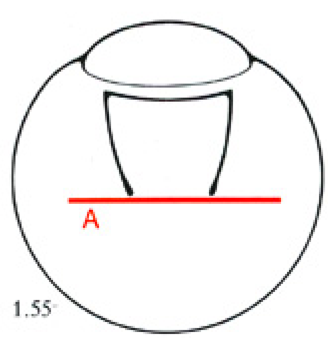
Fig. 1.54. **Reducing the dome height over the "hinge" by dividing the flap into segments.** Dividing a scleral flap into multiple subsegments shortens the distance between the wound ends for each segment. The dome heights over the subsegments are smaller than over the complete flap. *A* Hinge of entire flap, *B* axes of its subsegments

Fig. 1.55. **Reducing the dome height by converging the ends of the incision.** If the base of a scleral flap is made narrower than its free border, the hinge line is shortened as the dissection proceeds, and the depth of the fold is decreased



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1.3.6 Margin of Deformation

Obviously the globe cannot be totally protected from the effects of deforming forces. Yet clinical experience shows that not every deformation does jeopardize the surgical goal. Some degree of deformation can be tolerated in each phase of the operation, and this degree, which can be defined and quantified, is called the *margin of deformation*. It determines the necessary precision of surgical manipulations.

The margin of deformation that is available in a given case depends on the *surgical goal*. If the *pressure chamber is intact* (e.g., if the globe has not been punctured or incised), the margin of deformation is determined by the pressure that the ocular wall can withstand. If the *chamber is open*, the margin of deformation equals the volume of material that may escape from the eye without compromising the surgical goal. If **any volume loss** is unacceptable, the margin of deformation is zero. If the **loss of aqueous** is acceptable, the margin of deformation equals the volume of the anterior chamber. If **removal of the lens** is also proposed, the margin of deformation is increased by the lens volume. Finally, if **vitreous loss** is also compatible with the surgical goal, the margin of deformation equals almost the entire volume of the globe (Fig. 1.56).

A *large* margin of deformation is an important safety factor and gives the surgeon great freedom in selecting a procedure. On the other hand, a *small* margin of deformation limits surgical options, for it excludes any procedure that would deform the globe to an unacceptable degree. Increasing the margin of deformation, then, is an important aspect of *safety strategy* in ophthalmic operations. There are two ways of increasing the margin of deformation for the **pressure chamber of the entire globe:** One is to increase the strength of the ocular wall by providing a more secure wound closure that will withstand a higher pressure. Another way is to lower the intraocular pressure so that a greater volume displacement would be needed to produce a critical rise in pressure. This can be accomplished by reducing the production of aqueous[39] or by reducing the volume of vitreous.[40]

If the **globe is opened** and it is necessary to preserve the integrity of the vitreous chamber, there is only one way to increase the margin of deformation: by *reducing the vitreous volume*. The reduction of aqueous secretion is of no value in this situation.

One point cannot be overemphasized: *The margin of deformation is not a static quantity*. It changes continually during the course of an operation. All planned manipulations that have deforming vector components (see Fig. 1.45a) as well as all unplanned deformations consume a portion of the original safety margin. As a result, the tolerance to deformations may decrease as the operation proceeds.

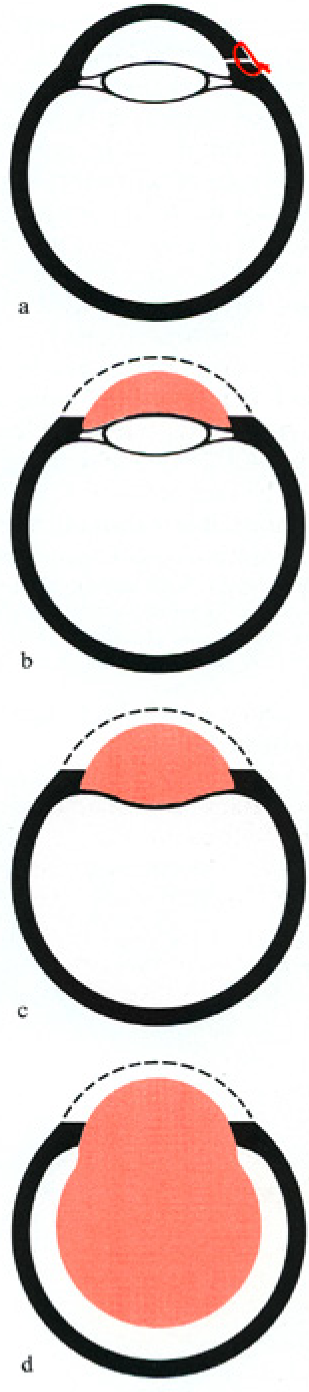
a b c d

Fig. 1.56. **Margin of deformation**

a If the goal is to preserve the total intraocular volume, no loss of fluid or tissue is acceptable, and the margin of deformation is zero. The force that the globe can tolerate is determined by the pressure that the wound closure can withstand.

b If the goal is to preserve the vitreous chamber, aqueous loss is acceptable, so the margin of deformation equals the volume of the anterior chamber.

c If the goal is to preserve the vitreous chamber, and lens extraction is proposed, the margin of deformation is increased by the volume of the lens.

d If vitreous loss is acceptable, the margin of deformation equals practically the whole intraocular volume

[39] Example: Carboanhydrase inhibitors.
[40] Example: Osmotically active substances, ocupression.

The surgeon, then, must closely monitor the available margin of deformation throughout the operation. It is the measure by which he must plan the procedure, and it tells him when he must switch to techniques that cause less deformation. A sudden decrease in the margin of deformation[41] is an important **warning sign**. If it is caused by the surgical measures themselves, the remedy is to change at once to techniques that have less deforming vector components.[42] If a sudden decrease in the margin of deformation cannot be ascribed to surgical manipulations, it must result from occult deforming forces that must be immediately identified and brought under control.[43]

1.3.7 Summary of Safety Strategy for External Forces

Deformations by external forces can be utilized to achieve specific goals, i.e., pressures can be raised to effect the *deliberate* expression of tissues (e.g., the lens or its nucleus). *Unintended* deformations, however, are a major source of complications, for they lead to inadvertent tissue expulsions (e.g., iris or vitreous prolapse). The goal of the safety strategy is to protect the intraocular compartments from the effects of unplanned forces.

The immediate goal of protective measures is to eliminate from the outset forces that cause unintended deformations of the ocular chambers (**prevention**). Therefore, the first step to safe surgery is the careful *preparation of the operative field* (see Chap. 3). During the operation, planned forces are applied in ways that cause minimal deformation, i.e. *positioning movements* are performed about the center of rotation of the globe (Fig. 1.44c), and *working movements* are applied tangentially (Fig. 1.45b). Deformation by hinge folds is prevented by employing techniques that do not require the elevation of flaps or, if a flap must be raised, the incision is tailored in a way that prevents excessive infolding or inversion of the ocular wall (see Fig. 1.51d, 1.54, 1.55).

Because total prevention is impossible, **defensive** measures are implemented to resist the deforming forces and protect the chambers from their effects. The ocular wall may be reinforced externally by attaching a *corset system* or internally by the introduction of *viscoelastic material*.

Because all these measures are of limited efficacy, every attempt is made to **increase the tolerance** of the chambers to deformations. A **large margin of deformation** is the most important safety factor that can be provided. Preoperative measures that reduce the pressure or volume of the vitreous establish the baseline margin of deformation. The *intraoperative* safety strategy is to stay within these established limits by avoiding any deformations that are not essential to accomplishing the surgical goal.

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[41] Evidenced, for example, by a rise of intraocular pressure or vitreous pressure (i.e., forward movement of the diaphragm, see Fig. 1.40b).

[42] E.g., instrumenting parallel to the ocular surface rather than perpendicular to it, avoiding techniques that cause expression.

[43] E.g., the contraction of extraocular muscles, choroidal hemorrhage ("expulsive hemorrhage").

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