Technical Aspects and Clinical Usage of Keplerian and Galilean Binocular Surgical Loupe Telescopes used in Dentistry or Medicine

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Abstract

Dentists often use unaided vision, or low-power telescopic loupes of 2.5-3.0x magnification, when performing dental procedures. However, some clinically relevant microscopic intra-oral details may not be visible with low magnification. About 1% of dentists use a surgical operating microscope that provides 5-20x magnification and co-axial illumination. However, a surgical operating microscope is not as portable as a surgical telescope, which are available in magnifications of 6-8x. This article reviews the technical aspects of the design of Galilean and Keplerian telescopic binocular loupes, also called telemicroscopes, and explains how these technical aspects affect the clinical performance of the loupes when performing dental tasks. Topics include: telescope lens systems, linear magnification, the exit pupil, the depth of field, the field of view, the image inverting Schmidt-Pechan prism that is used in the Keplerian telescope, determining the magnification power of lens systems, and the technical problems with designing Galilean and Keplerian loupes of extremely high magnification, beyond 8.0x. Other topics are also covered, such as what determines the width of the lenses of a telescopic loupes system, what determines the length of the telescope barrel, and how to calibrate the loupes working distance, and why the lenses of a Galilean telescope are shaped differently from a Keplerian telescope.

Introduction

Arguably, many clinically relevant visual details, that a dentist must observe to be able to diagnose and treat dental problems rationally, are microscopic, requiring magnification of 6-20x for them to be seen.[1-7] Simple examples include microscopic cracks in teeth,[7] microscopic root canal orifices,[8] and microscopic amounts of dental caries at the margins of restorative preparations.[4] Most dentists, however, use unaided vision or sub-microscopic 2.5x-3.0x magnification loupes when performing dental work, while approximately 1% of dentists use a surgical operating microscope.[2] Microscopes provide higher magnification than telescopic loupes and more powerful illumination, powered by an electric outlet.[2] However, telescopic loupes, combined with head-mounted, battery-powered, LED lighting, are more portable than the surgical operating microscope and allow a dentist greater freedom in moving the head and the body while working.

This article reviews the mathematical and technical aspects of the design of telescopic loupes,[9-14] showing how these aspects affect the clinical experience of using loupes while performing dental work, and explores the practicality of extremely high magnification Keplerian loupes, such as 10x or greater.

Important functional qualities of a telescopic loupes include the weight, the magnification power, the working distance (the distance in front of the loupes where an object must be located for it to be in focus) and the length of the barrel of the loupes.

The working distance of the loupes (along with the declension angle of the loupes, or the downward angle that the loupes barrel makes with the nose, and the height of the loupes barrel mounting on the nose bridge) determines how much the dentist must bend the neck and back in order to focus an intra-oral image.[15] Ideally, the working distance allows a dentist to bend the neck and back in a way that does not constitute a harmful posture.[16-17] The longer the working distance, the less spatter the dentist is exposed to while working. Also, the longer the working distance, the less intense is the illumination of the working site from a co-axial light that is mounted on the loupes, since the light travels a longer distance to reach the intra-oral work site. Finally, due to a concept called linear magnification, also called relative distance magnification, the longer the working distance, the less the effective magnification of a telescopic loupes system, for a given magnification value. For example, an 8x surgical telescope, calibrated to a 550 mm. working distance, effectively magnifies less than the same 8x surgical telescope calibrated to a shorter 450 mm. working distance.

Longer telescopic loupes barrels put more torque and weight on the bridge of the nose, are less aesthetic, and are more likely to be accidentally bumped into, compared to shorter length loupes barrels. The barrel length is affected by the number of lenses used and their respective diopter values, the spacing between the lenses, and whether or not a prism is needed in the lens arrangement. Generally, the higher the loupes magnification, the longer the barrel length; the barrel length of an 8.0x Keplerian loupes is approximately 9.0 cm.

A Single Lens Optical System

A simple lens system can consist of one object and one convex, positive, light-converging lens (**Fig. 1**). Light travels from the object and reaches the lens, which then focuses the light from the object to form an image of the object. The distance of the image of the object from the lens is determined by the quantity of divergence of light that is traveling from an object, and also by the strength of the lens.

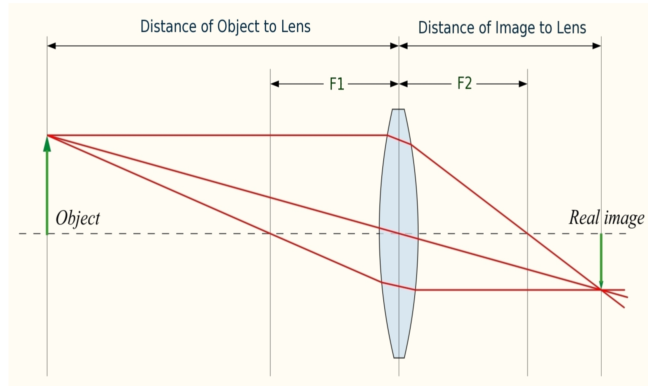

Fig. 1: Diagram of an optical system consisting of a single convex lens and an object (O), the primary (F1) and secondary (F2) focal lengths of the lens, and the location of the image (I) of the object. (Diagram courtesy of Dr. Robert Mellish, modified from the Wikipedia Commons)

The "simple lens formula,"

$$U + D = V$$

is used to calculate the distance of the image of the object from a lens, where:

U is the diopter value of the divergence of light that is emanating from an object, and equals:

100 cm. / the distance in centimeters that light travels from the object before it reaches the lens

(The "U" value is usually negative because light diverges as it travels from an object towards the lens.)

D is the diopter value of the lens, a measure of how strongly the lens bends or refracts light.

V is the total value of divergence (or convergence) of light after it emanates from the object, moves a specified distance through air to the lens, and passes through the lens.

After obtaining V, the distance of the image of the object from the lens = 100 cm. / V

A convex lens causes light from an object located at infinity to *converge* to a focal point (located behind the lens), so a convex lens has a *positive* diopter value. A concave lens causes the parallel light that passes through it to *diverge*, resulting in a virtual focal point (located in front of the lens), so a concave lens has a *negative* diopter value.

For example, if an object is located 25 cm. in front of a lens with a value of +5 D,

U = -100 cm. / 25 cm. = -4;
D = +5;
V = U + D = -4 + 5 = +1;

The image of the object is therefore located 100 cm. / V = 100 cm. / +1 = 100 cm. behind the lens.

Primary and Secondary Lens Focal Points

Each lens has a primary and a secondary focal point.

The primary focal point of a lens (also called the object space focal point) is by definition the point where, if an object was located at that point, the light from the object, after it passed through the lens, would emerge from the other side of the lens parallel and collimated. The primary focal point for a convex lens is located a distance of:

100 cm. / D

in front of the convex lens.

The secondary focal point of a lens (also called the image space focal point) is by definition the point where the lens focuses light that reached the lens from an object located an infinite distance from the lens. The secondary focal point of the convex lens, like the primary focal point, is also located a distance of:

100 cm. / D

but is located behind the convex lens.

The location of the image of the object may or may not coincide with the location of the secondary focal point of the lens. As the U + D = V equation shows, if the object is located an infinite distance from the lens, it will have a U value of 0, so that the location of the image of the object will coincide with the location of the secondary focal point of the lens. However, if the object is located near the lens and in front of the primary focal point of the lens it will have a U value that will result in the image of the object being a different distance from the location of the secondary focal point of the lens.

Overview of Telescopic Loupes

The logic of a one lens and one object system facilitates understanding how the lens system of a Galilean or Keplerian telescopic loupe is constructed.

A telescope accepts the light from an object that is located at an infinite distance, and focuses the light through a lens system such that the image of the object is much smaller than the actual object, but also such that the image of the object is located much closer to the observer, resulting in the object appearing magnified.

In a telescope lens system, consisting of an objective lens and an eyepiece lens, the secondary focal point of the objective lens (the lens that is closest to the object being viewed) must coincide with the primary focal point of the eyepiece lens (the lens closest to the observer's eye), in order for light rays to exit the telescope eyepiece parallel and collimated.

The objective lens of the telescope images an object that is located an infinite distance from the telescope, and focuses the image at the secondary focal point of the objective lens. Since the secondary focal point of the objective lens coincides with the primary focal point of the eyepiece lens, the image of the object formed by the objective lens becomes the “object” that the eyepiece lens images. Since this “object” is located at the primary focal point of the eyepiece lens, the light of the image of this “object” emerges from the eyepiece as a parallel and collimated light column. Telescopes are termed “afocal” optical systems because when parallel light from a real object enters the telescope, it leaves the telescope also parallel.

Galilean Telescopic Loupes

The Galilean telescope consists of two lenses; a concave eyepiece lens and a convex objective lens. The eyepiece lens is stronger (i.e. has a higher diopter value) than the objective lens.

The objective lens, with a smaller diopter value, has a longer focal point distance compared to the eyepiece lens, given the formula

$$100 \text{ cm.} / D = \text{focal distance.}$$

Light from an object passes through the objective lens and then focuses at the secondary focal point of the objective lens. Since the eyepiece lens is a concave lens, the primary focal point of the eyepiece lens is actually located behind the eyepiece lens. Since the Galilean telescope lenses are arranged such that the primary focal point of the eyepiece lens is coincident with the secondary focal point of the objective lens, the secondary focal point of the objective lens is also located behind the eyepiece lens. Consequently, the light passing through the objective lens must also pass through the eyepiece lens, in order to reach the secondary focal point of the objective lens. Then, due to the physics of how a concave lens bends light, the image formed by the concave lens, that contains the light that the observer's eye actually sees, originates in front of the concave (eyepiece) lens, between the two lenses of the Galilean telescope. (**Fig. 2**)

In other words, the light pathway that emanates from the objective lens until it reaches the point of the secondary focal point of the objective lens, is "superimposed" upon the light pathway that emanates from the primary focal point of the eyepiece lens until it reaches the eyepiece lens. Due to this "super-imposition," the distance between the two lenses is relatively short. Consequently, for a given magnification power, the length of the telescope barrel is shorter for Galilean telescopes compared to Keplerian telescopes, where these two specific light pathways are not superimposed but are arranged linearly one after the other.

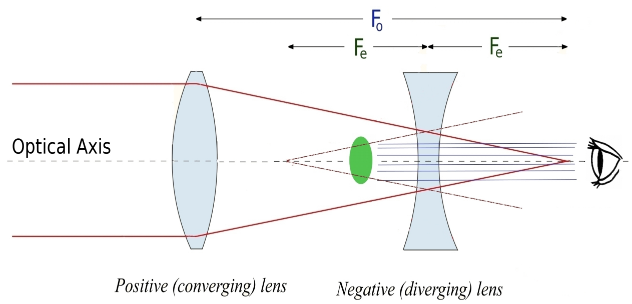

Fig.2: Simplified lens schematic of a Galilean telescope with a convex objective lens and a concave eyepiece lens, where the exit pupil (green oval) originates inside of the telescope.

Determining a Galilean Telescope Length

The length of the Galilean telescope barrel, which is essentially the distance separating the eyepiece and the objective lenses, equals the distance of the objective lens to the secondary focal point of the objective lens minus the distance of the eyepiece lens to the primary focal point of the eyepiece lens:

$$d = F_o - F_e$$

For the length of a Galilean telescope barrel to be short, the telescope lenses must have short focal distances. Hence, Galilean telescope loupes are made using lenses of strong diopter values, since a focal distance of 100 / D is shorter for higher lens diopter values.

For example, if a Galilean telescope has an eyepiece lens of -50 D and an objective lens of +20 D, the distance from the objective lens to the secondary focal point of the objective lens = 100 cm. / +20 = 5 cm. The distance from the eyepiece lens to the primary focal point of the eyepiece lens = 100 cm. / D = 100 cm. / +50 = 2 cm. The distance between the lenses is 5 - 2 = 3 cm. The specific point, of this Galilean loupes system, where the secondary focal point of the objective lens coincides with the primary focal point of the eyepiece lens, is located 5 cm. behind the objective lens, and also 2 cm. behind the eyepiece lens.

Magnification of Galilean Telescope

The formula for the magnification of a Galilean Telescope is:

$$M = - F_e / F_o$$

where F_e is the diopter value of the eyepiece lens, and F_o is the diopter value of the objective lens.

Since the eyepiece lens is concave in shape and has a negative diopter value, the magnification of a Galilean telescope, given that the telescope magnification formula has a default (-) sign, is a positive value. A positive magnification value indicates by convention that the image formed by the Galilean telescope is upright. Since the image is upright by default, an uprighting prism (which adds weight to the Galilean telescope) is not needed in a Galilean telescope.

Keplerian Telescopic Loupes

Unlike Galilean loupes, Keplerian loupes consist of two or more positive convex lenses. Keplerian telescope lenses are arranged such that the secondary focal point of the objective lens coincides with the primary focal point of the eyepiece lens. This point is located between the two lenses, instead of behind both lenses, as it is with Galilean loupes.

Light from the object passes through the objective lens, focuses at the secondary focal point of the objective lens, and moves from this focal point (which is also the primary focal point of the eyepiece lens) to the eyepiece lens, and then emerges from behind the eyepiece lens as a parallel and collimated beam. **(Fig. 3)**

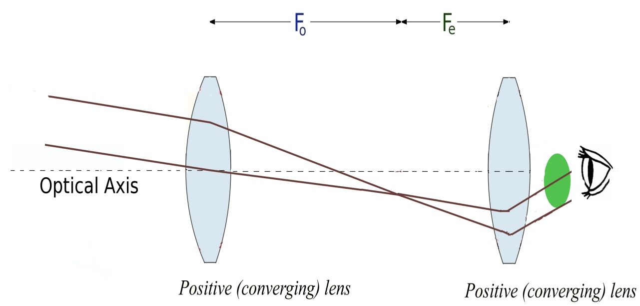

Fig. 3: Simplified schematic of a Keplerian telescope with two convex lenses, showing the exit pupil (green oval) originating behind the eyepiece lens, outside of the telescope.

Hence, unlike with Galilean telescopes, light from the objective lens first focuses to the secondary focal point of the objective lens before it passes through the eyepiece lens, instead of passing through the eyepiece lens before focusing at the objective lens secondary focal point. These focal distances are not superimposed on one another as they are with Galilean loupes. Consequently, the length of the Keplerian telescope barrel is determined by adding the distance from the objective lens to the secondary focal point of the objective lens, with the distance from the primary focal point of the eyepiece lens to the eyepiece lens. Consequently, for a given magnification level, the length of the barrel of Keplerian telescopic loupes is longer than that of Galilean loupes.

Since the two lenses of a Keplerian telescope are positive in value, the magnification they produce, according to the equation:

$$M = - F_e / F_o$$

is negative. A negative magnification value means that the image formed by the two lenses is not upright but is instead inverted 180 degrees. Consequently, Keplerian loupes require an extra component, called a prism, in order to make the inverted image upright.

The prism of a Keplerian telescope must be able to fit inside the cylindrical telescope barrel. The prism must allow light rays to enter one end of the prism, must invert the light rays 180 degrees, and then must allow the light rays to exit the prism from the other end while keeping the axes of the exiting light rays co-axial with the axes of the entering light rays. In a Keplerian telescope, the Schmidt-Pechan prism performs these functions. It consists of two separate prisms: a Schmidt prism that is stacked onto a Pechan prism. Incoming light rays enter the Pechan prism, which deviates the rays by 45 degrees without inverting the rays, and directs the rays into the Schmidt prism that is stacked above the Pechan prism. The Schmidt prism then inverts the rays and deviates them by -45 degrees. The exiting light rays are therefore inverted, but deviated by a net of 0 degrees, so that the exiting rays remain on the same axes as were the entering rays. (**Figs. 4 and 5**)

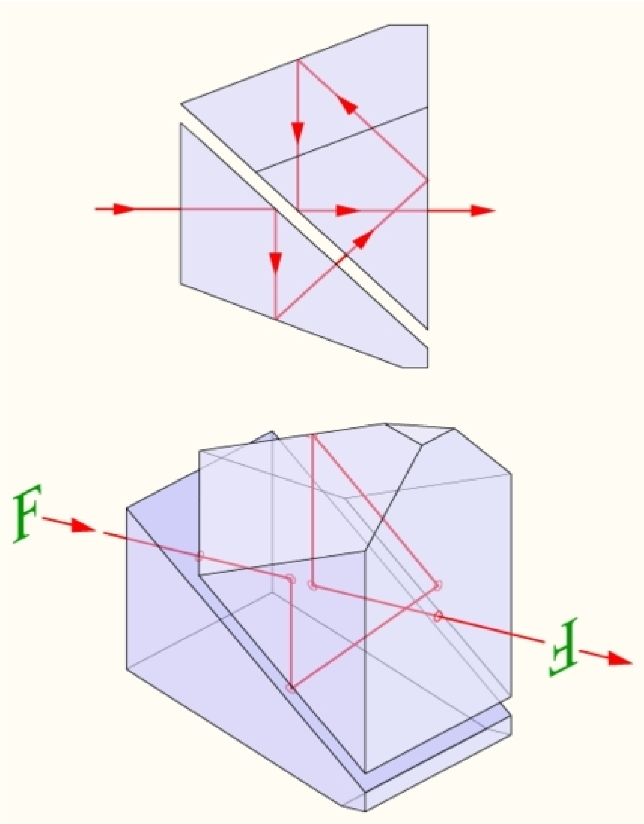

Fig. 4: Diagram of a Schmidt-Pechan prism, consisting of two separate prisms stacked one over the other, showing the path of light through the prism and the inversion of the image. (Drawing courtesy of Dr. Robert Mellish, from the Wikipedia Commons)

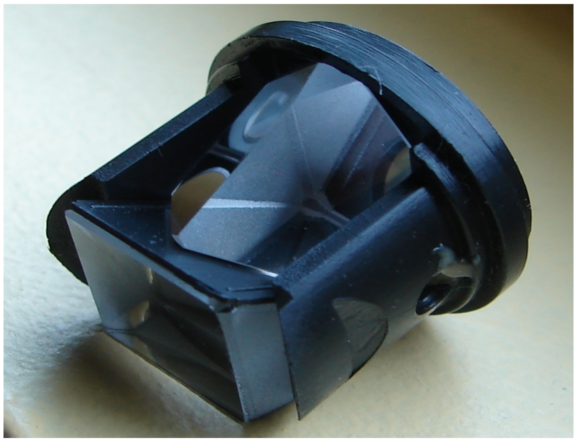

Fig. 5: Example of a Schmidt-Pechan prism, placed in a cylindrical plastic housing that allows it to fit inside the cylindrical Keplerian loupe barrel.

Consider a 2x Keplerian surgical telescope with an eyepiece lens of +50 D and an objective lens of +25 D. The secondary focal point of the objective lens is located 100 cm. / 25 = 4 cm. inside the telescope. The primary focal distance of the eyepiece lens is 100 cm. / 50 = 2 cm. Since the focal points of the two lenses inside the telescope must be aligned with one another, the total length of this Keplerian telescope (excluding the prism length) is 4 cm. + 2 cm. = 6 cm.

Calibrating the Loupes Working Distance

By default, an afocal telescope focuses light only from objects located an infinite distance away from the objective lens. To adjust the telescope such that, instead, it focuses objects that are nearby, an extra lens called a "reading lens" must be added to the lens system, to result in the objective lens focusing the image of the nearby object at the secondary focal point of the objective lens. Specifically,

Diopter value of reading cap required = 100 / Desired working distance of the telescope in cm.

For example, if the required working distance of the loupes is 400 mm., or 40 centimeters, an object placed at this distance would have a U value of -100 / 40 = -2.50 D. The diopter value of the "add" that must be added to the afocal telescope to make it focus an object located at a 400 mm. distance is therefore +2.50 D. This +2.50 D reading cap would be placed next to the objective lens or, alternatively, a single objective lens can be made with an extra +2.50 D of value added to the lens in addition to the value that the objective lens would have had if the telescope was afocal.

For example, to calibrate an afocal 2.5x Galilean telescope with a -50 D eyepiece and a +20 D objective lens such that it has a working distance of 500 mm., or 50 cm., the required diopter value of a reading lens would be 100 cm. / 50 cm. = +2 D. A designer could change the diopter value of the objective lens to +20 + 2 = +22 D to create a 2.5x Galilean telescope with a working distance of 500 mm.

Here, the designer keeps the distances between the lenses the same with the new telescope as the distances were with the old telescope.

The working distance of the loupes (along with the declension angle of the loupes, or the downward angle that the loupes barrel makes with the nose, and the height of the loupes barrel mounting on the nose bridge) determines how much the dentist must bend the back and neck to bring an intra-oral object into focus.[16-18] The longer the working distance, the less spatter the dentist is exposed to while working. Also, the longer the working distance, the less intense is the illumination of the work site from a loupes-mounted light source, since the light must travel a longer distance to reach the work site.

Linear Magnification

When a dentist orders a telescopic loupes of a given magnification value, the loupes factory offers the dentist a choice of what working distance to calibrate the loupes at, such as 340 mm., 420 mm., or 550 mm. The dentist should be cautious when choosing the working distance, because changing the working distance of the loupes, via calibration with a reading cap, also changes the effective magnification of the loupes. Calibrating the loupes to focus at an increased working distance results in a proportional linear decrease of the retinal image size created by the loupes. This is because an object appears larger (and hence more "magnified") if it is physically closer to the objective lens of the loupes, a phenomenon termed “linear magnification.”

The relative change in the retinal image size of a telescope of a certain power, due to an adjustment of its working distance, is given by the formula:

$$M = X / X'$$

where X is the old focal distance and X' is the new focal distance.

For example, an 8.0x Keplerian loupes, calibrated to a working distance of 420 mm., provides a higher effective magnification compared to another 8.0x Keplerian loupes calibrated to a working distance of 550 mm. The retinal image size of the former is 550 mm. / 420 mm. = 1.31 times the retinal image size of the latter. To have the same retinal image size of an 8.0x telescopic loupes that is calibrated to 420 mm., a telescopic loupes, that is calibrated to 550 mm., would actually require a higher native magnification of approximately 1.31 times the 8.0x magnification, or approximately 10.48x magnification.

The decrease in retinal image size provided by loupes, that results from a dentist choosing to calibrate a loupes of a given magnification at an increased working distance, could affect the dentist's clinical performance when using these loupes. The resulting decreased effective magnification may, for example, cause the dentist to create more microscopic undercuts in crown preparations[18] resulting in more minutes needed to adjust crowns at the insertion appointment.

Relative Size Magnification

Due to a phenomenon called relative size magnification, larger-sized objects result in larger images when viewed through a telescope of a given magnification compared to smaller-sized objects. If one patient has a larger maxillary first molar than another patient, the image of the maxillary first molar of the first patient appears larger in size than that of the second patient.

The Exit Pupil in Loupes Design

All of the points of light that are focused by the eyepiece lens collectively form an image that appears as a round area of light. This area of light, which appears to "float" above the eyepiece lens, is called the "exit pupil" of the lens system,[12] and is what the eye sees when looking through the eyepiece. (**Fig. 6**)

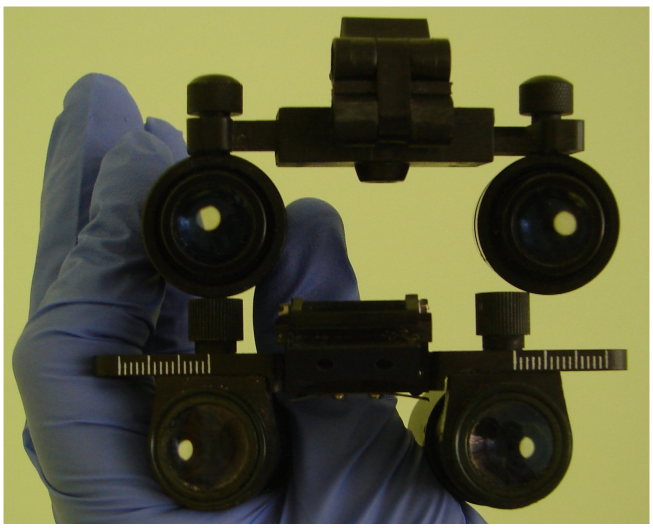

Fig. 6: The exit pupils emanating from the eyepieces of a 4x (top) and a 6x (bottom) Keplerian binocular loupes are the small circles of light that appear floating in space in above the eyepieces. Here, the exit pupils of the 4x loupes have longer radii (and consequently diameters) compared to the exit pupils of the 6x loupes.

Also, the pupil of the observer's eye functions as an opening (or aperture) that accepts the light of the exit pupil of the lens system. The eye pupil aperture (also called the "entrance pupil of the eye") is approximately 4-5 mm. in diameter, although in some eyes the pupil is larger or smaller in diameter.

Ideally, a surgical telescope projects an exit pupil that is the same diameter as the entrance pupil of the observer's eye, onto the entrance pupil of the observer's eye. The "eye relief" distance of an optical instrument, is the distance from the observer's eye to the eyepiece, such that if the observer's eye is positioned at this distance, the exit pupil of the telescope becomes superimposed on the entrance pupil of the observer's eye. Typically, an optics engineer tries to design a binocular loupe that forms an exit pupil that is located about 20 mm. behind the eyepiece surface. This is for many observers a comfortable distance to position the eye from the eyepiece of a surgical telescope.

As the observer's eye approaches the eye relief distance, the image of the exit pupil appears to suddenly enlarge and occupy the observer's field of view, since the exit pupil is the only image that the entrance pupil of the eye sees. If a binocular loupe slips down the nose bridge due to poorly gripping nosepads, this slippage may increase the distance of the exit pupil from the observer's eye, such as to noticeably decrease the perceived size of the image.

Calculating the location of the exit pupil is somewhat complicated.[11] From the edge of an object emanates a type of light ray called a principle ray. The principle ray is bent by the lenses of the lens system such that, as it passes through the lens system, it sometimes is located above the optical axis or optical center of the lens system, and sometimes is located below this optical axis, and at various points this principle ray intersects the optical axis. Essentially, the exit pupil of the lens system is located at one of these intersection points, in front of the eyepiece for a Galilean telescope, and behind the eyepiece for a Keplerian telescope.

The width of the exit pupil is determined by the following formula:

The exit pupil width = Diameter of objective lens in mm. / Magnification of the lens system

If the exit pupil formed by the lens system is smaller in diameter than the entrance pupil of the observer's eye, then when looking through the eyepiece, the observer will see a small, and possibly too small, image of the object surrounded by a dark circle or vignette.

With a Galilean telescope, the exit pupil is located inside the Galilean telescope, between the two lenses of the telescope. Therefore, the exit pupil of the Galilean telescope is not located at the same location in space as is located the entrance pupil of the observer's eye, but instead is located some distance in front of the entrance pupil of the observer's eye. Consequently, the exit pupil of a Galilean telescope must be wider than 4-5 mm. in diameter to compensate for the exit pupil being located further from the eye. This requires that the Galilean objective lens be of a relatively large diameter.

A Galilean telescope with a 20 mm. diameter objective lens and 2.0x magnification results in an exit pupil of 20 / 2.0 = 10 mm. in diameter. A Galilean telescope with 4.0x magnification requires an objective lens of 40 mm. diameter to maintain a 10 mm. diameter exit pupil, while a 6.0x Galilean telescope requires a 60 mm. diameter objective lens. Since objective lenses of these sizes are wide, heavy and expensive, the magnification of a Galilean telescope is limited[20] to the 2.0-3.5x range.

With a Keplerian telescope, unlike a Galilean telescope, the exit pupil is formed behind the eyepiece lens. Consequently, the location in space of the exit pupil of the lens system is closer to being superimposed on the location in space of the entrance pupil of the observer's eye. Hence, the diameter of the exit pupil of a Keplerian telescope does not have to be larger than 4-5 mm. in order to compensate for an increased distance of the lens exit pupil from the eye entrance pupil, as is required with Galilean telescopes. Therefore, the diameter of the objective lens of a Keplerian telescope, for a given telescope magnification value, is smaller compared to the diameter of the objective lens of a Galilean telescope. (**Fig. 7**)

Fig. 7: A 2.5x Galilean binocular loupe (lower left), and a 4x (top left) and a 6x (right) Keplerian binocular loupe shows the longer barrel length for higher magnification Keplerian binocular loupes, and the wider diameter objective lens of the Galilean binocular loupes.

Depth of Field

The depth of field or "blur circle" is a range of distances that the objective lens can be from an object such that the object will be focused by the lens system of that objective lens. The higher is the magnification of a surgical telescope, the smaller will be the depth of field. The smaller the depth of field, the more exactly the dentist must position the objective lens from an object in order for the object to appear in focus. For a small depth of field, it may be difficult for a dentist to keep the head steady enough to prevent the telescope from moving out of the range of the depth of field.

Field of View

The field of view is essentially the portion, measured in angles, of the total possible visual field (i.e. a 360 degree visual field) that is visible through a lens arrangement.[21] A human using unaided vision can see essentially everything from right to left, giving a 180 degree field of view.

The Telescope field of view = Field of view of the eyepiece / Magnification of the telescope

An eyepiece typically has a field of view in the range of 50-60 degrees. Since the field of view is inversely proportional to the magnification of the telescope, a telescope with 10x magnification provides a field of view of about 5-6 degrees. With magnifications of 12-15x, the field of view may be as low as 2 degrees. Since this is a small proportion of the total visual field, a dentist must have good spatial sense to determine where in the mouth is the location that corresponds to the tiny slice or circle arc of image that the dentist is seeing, to relate the image seen with the overall visual context, and also to possess a sense of measurement while working in this tiny visual field.

Designing Loupes Lens Schematics

The decision-making process of selecting a combination of lenses to achieve a specified magnification power of a telescopic loupe requires making compromises. The formula

$$M = - F_e / F_o$$

provides a guide of what diopter value of lenses are needed. To make a 12x Keplerian loupes, for example, one can theoretically use eyepieces of 48 D and an objective lens of 4 D. However, since a 4 D lens has a focal distance of 25 cm, the length of the barrel of the loupes will be at least this long, plus the approximately 2 cm. focal distance of the 48 D eyepiece, plus the approximately 1 cm. length of the erecting prism used in the loupes, making a total length of 28 cm., which may be impractical.

A designer could use stronger diopter lenses, that have smaller focal distances, to try to shorten the loupes barrel length, such as by producing a Keplerian telescope with a 20 D objective and a 240 D eyepiece. This would give a telescope barrel length of about 6-7 cm. However, the 240 D eyepiece would be so strong that it may feature aberrations (or image distortions) often found in such a powerful lens.

Instead of using a single extremely strong lens, a designer can use multiple lenses of smaller diopter values each to create the same magnification provided by the extremely strong lens. However, multiple lenses may make the telescope heavier and more expensive to manufacture.

The size of the exit pupil of the system is another concern. A 20 mm. diameter objective lens, divided by 12x power, gives an exit pupil of less than 2 mm. in diameter.

One can also produce a Keplerian telescope of a higher magnification by combining the lenses of two Keplerian systems of lower magnification. The magnification value of the new Keplerian telescope is found by multiplying the values of the individual telescopes used to make it. For example, combining the lens systems of a 4x Keplerian telescope with a 5x Keplerian telescope produces a Keplerian telescope of 20x magnification.

Conclusion

This article introduced the basic theoretical principles behind the design of magnifying telescopic surgical binocular telescopes that are used in dentistry or medicine. In the practical world, computerized lens programs are often used to develop theoretical models of lens arrangements for achieving a desired magnification and working length values. A promising design is then prototyped and evaluated to determine if the design is clinically practical.

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