# Pinhole Photography

## The fascinating world of lensless imaging

A number of dedicated individuals paved the way for the invention of photography with their accomplishments in several areas of the natural sciences. However, in very basic terms, photography requires only one condition to be satisfied, the successful combination of image formation and image capture.

Image capture has been in the chemical domain for over 150 years, but modern electronics recently added digital image capture as a realistic alternative and provided us with fresh tools for image manipulation. Image formation, on the other hand, was always governed by the laws of optics. It may be of historic interest to note that image formation and capture were practiced independently for some time, before they were successfully combined to make photography

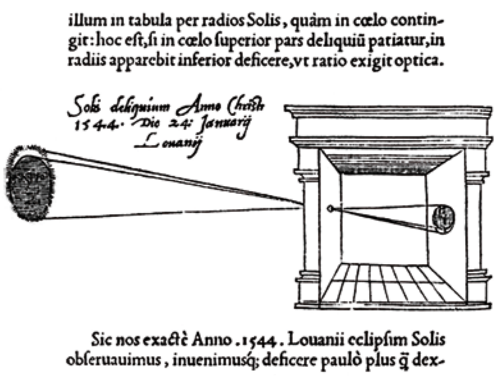



fig.1 (top) This is thought to be the first published picture of a camera obscura and a pinhole image, observing the solar eclipse of 1544-Jan-24, in the book *De Radio Astronomica et Geometrica* of 1545 by Gemma Frisius.

fig.2 (right) A print made with an 11x14-inch large-format pinhole camera shows surprising detail and clarity.

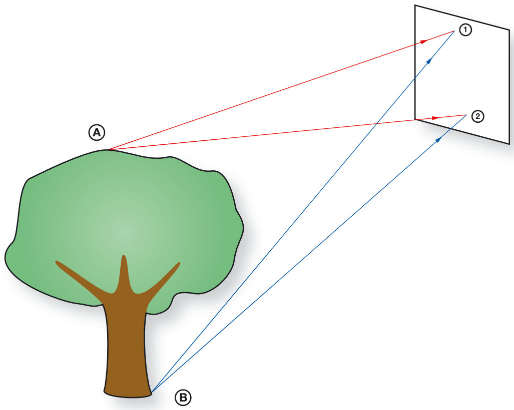



fig.3a Simply holding up a card in front of a subject is not sufficient to create an image, because every point on the card receives light rays from numerous points on the subject.

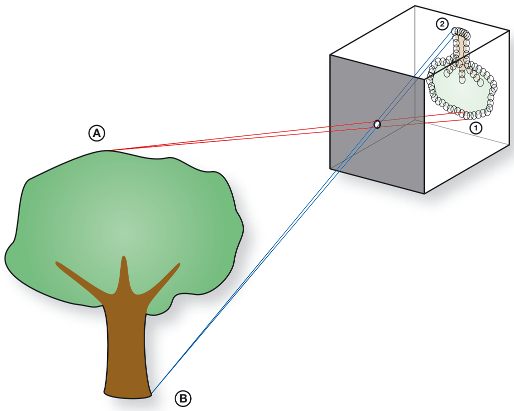



fig.3b But if an opaque panel, containing a tiny pin-sized hole, is placed between the subject and the card, the panel blocks all light rays coming from the subject with the exception of a limited number entering through the pinhole. The small hole restricts the light rays coming from the subject to a confined region, forming countless blurry image circles and a fuzzy image.

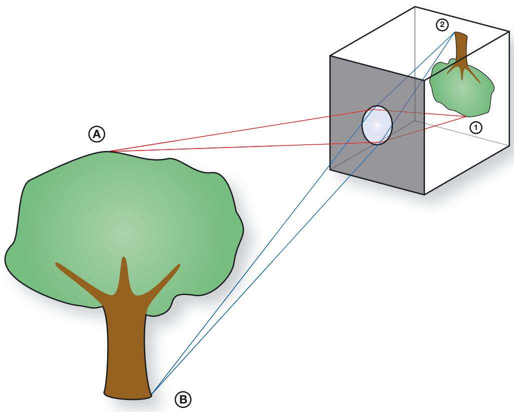



fig.3c To improve image quality, the pinhole is replaced by a lens. It converges several light rays from the same subject point into one focused image point. This makes for a sharper and brighter image than a pinhole can possibly provide.

possible. Nevertheless, taking a closer look at these building blocks of photography, one quickly finds that image formation is far older than image capture.

Basic image formation is as old as nature itself. The simplest arrangement for basic image formation is by way of a pinhole. The overlapping leaves in trees form numerous pinholes naturally, through which countless sun images are projected onto the ground. It is conceivable that humans were captivated by the crescent pinhole images of an eclipsed sun as early as the dawn of mankind.

The earliest known description of pinhole optics came from Mo Ti in China from around 400 BC, and Aristotle wrote about his observations of the formation of pinhole images in 330 BC. The first known proposals to create a small opening in an otherwise darkened room (camera obscura), in order to intentionally produce pinhole images, came from Alhazen in Egypt around 1020 AD and Roger Bacon (1219-1292) in England. Obsessed with representing realistic perspectives, Renaissance artists, including Leonardo da Vinci (1452-1519), often used a camera obscura to develop the early sketches for their magnificent paintings. In 1584, the second edition of Giovanni Battista Della Porta's book *Magia Naturalis* was published. In this book, he describes the formation of pinhole images and the construction of a pinhole camera in detail. Around that time, Johannes Kepler (1571-1630) coined the phrase camera obscura, which literally means 'dark room'. Soon after, many pinholes were replaced by a simple concave lens, which improved image brightness and quality. Pinhole imaging languished over 200 years, until after the invention of photography, to have its first revival around 1850.

## Image Formation

Image formation starts with light rays, which are either emitted or reflected by the subject. The light falling onto an opaque subject is partially absorbed and partially reflected. Theoretically, reflection is either directional (specular) or multidirectional (diffuse). In reality, the actual reflection depends on the surface characteristics of the subject and is always a mixture of specular and diffuse reflections. Smooth surfaces, such as glass, mirrors, polished metal or the calm surface of a lake, create predominantly specular reflections. Rough surfaces, such as leaves, stone, cloth or dry skin, create primarily diffuse reflections.

For the purpose of investigating general image formation, we can safely assume that every point of an illuminated subject emits or reflects light in multiple directions. Simply holding up a card in front of the subject is not sufficient to create an image on the card, because every point on the card receives light rays from numerous points on the subject (see fig.3a). Successful image formation requires a more structured approach of correlating subject with image points.

The simplest arrangement for image formation is achieved by placing a flat opaque object, containing a tiny pin-sized hole, between the subject and the card (see fig.3b). The opaque panel blocks all light rays coming from the subject with the exception of the few entering through the pinhole. The hole is small enough to restrict the image points on the card to light rays coming from a confined region of the subject, forming countless blurry image circles, which together form a dim fuzzy image. This way, compromised image formation is possible, because every potential image point receives light rays only from a limited number of subject points.

As we can see, expensive optics are not essential to the image-forming process, but to improve image quality beyond the pinhole, the light-restricting opening must be replaced by a convex lens. The lens converges several light rays from the same subject point into one focused image point through refraction (see fig.3c). This makes for a sharper and brighter image than a pinhole can possibly provide. High-quality image formation is only possible with a lens, where every potential image point receives light rays exclusively from its corresponding subject point. Nevertheless, pinhole photography offers a subtle beauty, which is difficult to achieve otherwise and, therefore, makes exploration and optimization of this fascinating field of photography worthwhile.

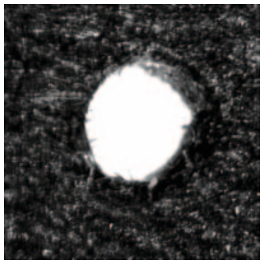
## Making Your Own Pinhole Camera

The first step in building a pinhole camera is to create the pinhole itself. A high-quality pinhole is accurate in diameter and has a smooth perimeter for superior image clarity. The smoother the edge of the pinhole is, the sharper the resulting pinhole image will be. You can buy a pinhole or make one yourself.

Several suppliers of optical and scientific products sell laser-cut pinholes, which are typically drilled into thin brass foil. Professionally made, laser-cut pinholes do not cost a lot, which makes them the best choice, because they are also extremely precise in diameter and have an exceptionally smooth edge (fig.4b). Nevertheless, if you are in a rush, or just want to experiment with a pinhole, you can simply take a pushpin or sewing needle and force it through a piece of black cardboard (fig.4a). This will make for a workable pinhole, but don't expect an optical miracle, because the rough edge will degrade image quality significantly.

If you aim for more accuracy, consider the following work instructions, illustrated in fig.5. This will not provide you with a pinhole of ultimate precision, but with a bit of practice and the right materials, a good-quality pinhole can be made within a few minutes.

1. Use scissors to cut a piece of metal from brass foil, or an aluminum can, roughly 15x15 mm in size.
2. Place the metal flat onto a soft wood support, and firmly press a ballpoint pen into the center of the square, creating a clearly visible indentation.
3. Turn the metal over, and use fine sandpaper to thin away the bump without penetrating the metal.
4. Create the pinhole by pushing a needle through the center of the indentation, and gently reinsert the needle from the other side to smooth the edge.



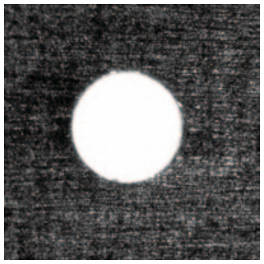


fig.4a (far left) Simply forcing a needle through a piece of cardboard will result in a workable pinhole, but the rough edge degrades image clarity.

fig.4b (left) A laser-cut pinhole, with a particularly smooth perimeter, gives the best possible image quality.

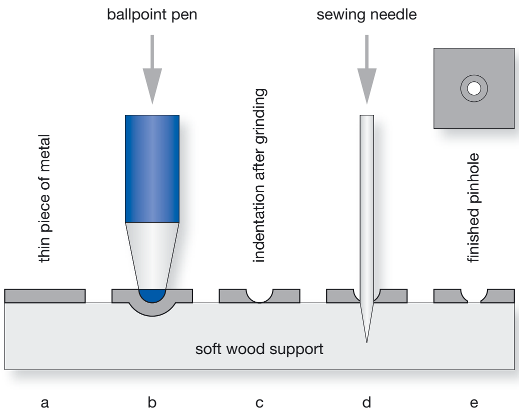



fig.5a (below left) With a little bit of practice and the right materials, a good-quality pinhole can be made in a few minutes.

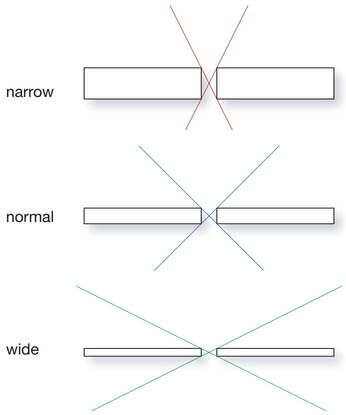



fig.5b (below) The pinhole material thickness limits the angle of coverage. Thick materials may reduce the angle of view, and the pinhole will no longer fill the entire negative format.

fig.6 Old medium-format camera bodies make perfect pinhole cameras. This shows a well-kept 6x9 box camera from around 1930 after the conversion.

fig.7 (far right) Pinhole images have an almost infinite depth of field combined with beautiful image softness. This image softness is partially caused by diffraction but also by motion blur during long exposure times, which are rather common for pinhole photography.

The pinhole material thickness is of some consequence to the pinhole image, because it limits the angle of coverage. A thickness of about 0.1 mm is ideal, because it provides an angle of over 125°. Thicker materials may reduce the angle of view, and the pinhole will no longer fill the entire negative format (see fig.5b).

It is a good idea to measure the pinhole diameter before the pinhole is mounted to the camera body. It is difficult to measure afterwards, and without knowing the size of the aperture, we cannot accurately determine the working f/stop of the pinhole camera. Unless you have access to a microscope with measuring capability, simply magnify the pinhole by any available means. Use a slide projector, the darkroom enlarger or a scanner to perform this task. First, prepare a measurement sample, for example two lines, known to be 20 mm apart, and enlarge or scan this sample to determine the magnification factor. Finally, enlarge or scan the pinhole at the same magnification, measure the projection or the scan and calculate the actual diameter of the pinhole. The working f/stop of the pinhole (N) is given by:

$$N = \frac{f}{d}$$

where 'd' is the diameter of the pinhole, and 'f' is the focal length of the pinhole, which is the distance between the pinhole and the film plane, assuming that a pinhole camera is always focused at infinity.

Almost any container can be turned into a pinhole camera body as long as it is absolutely light tight. Popular items include cardboard or metal boxes of all sizes, as well as cylindrical storage containers for food, chemicals or rolls of film. Everything from 35mm film canisters to full-size delivery vans has been converted to portable pinhole cameras. Best suited, and far more practical, are old camera bodies. They are already designed to safely hold and transport film, and with the exception of view cameras, most of them offer some kind of viewfinder to compose the image and a shutter to control the exposure.

Fig.2 shows a pinhole image that was taken with a self-made 11x14-inch large-format view camera. It takes minimal effort to convert a view camera into a pinhole camera. Temporarily mounting a pinhole into an empty lens plate is all one has to do to finish the conversion. This small endeavor is rewarded with large negatives and pinhole images of surprising detail and clarity, because the maximum possible resolution with contact-printed pinhole images (see fig.14) approaches the resolving power of standard human vision, which is around 7 lp/mm.

Medium-format box cameras offer an opportunity for a more permanent pinhole conversion. Old medium-format box cameras are available in abundance on the used-camera market and can be obtained for little money. However, be certain to hunt for a model that works with the common 120-film format. This format was introduced in 1901 by Kodak for their Brownie No.2 and is still manufactured today, because it is used in all modern medium format cameras. Fig.6 shows my medium-format pinhole camera, based on a well-kept Balda Poka, which was made in Germany around 1930. I paid less than $15 for it in an internet auction. The simple meniscus lens was removed and replaced with a 0.38mm laser-cut pinhole. This diameter is ideal for the 6x9 negative format and the 105mm focal length. The working aperture computes to f/278 or f/256 and a 1/3 stop. The shutter has two settings, 1/30 s and 'B'. For the long exposures, which are typical for the small apertures in pinhole photography, I use the 'B' setting exclusively and chose to keep the shutter open by securing the release lever with a rubber band.

The simple snapshot in fig.7, which was taken with the converted medium-format camera in fig.6, illustrates the almost endless depth of field in pinhole photography. When selecting a camera body for a pinhole conversion, be aware that many old medium-format cameras have a small red window at the back. This window is part of the manual film advance system and is provided to identify the current negative frame. The 120 roll-film format has the frame numbers of all popular medium negative formats printed on the outside of the backing paper, and they can be seen through the window. To protect the film from harmful light entering through the window, it is made of red-tinted glass or plastic. This protection works well for orthochromatic films but is not a reliable safeguard for modern panchromatic films. Before you load the camera with panchromatic film, cover the red window with a piece of black tape from the outside. Whenever you need to advance the film, shade the window with one hand and carefully pull the tape aside with the other. Then, advance the film to the next frame and quickly cover the red window with the tape again.

Analog or digital small-format SLRs are easily converted to sophisticated pinhole cameras by sacrificing an opaque body cap. The distance from the camera's lens mount flange to the film or focal plane is, therefore, an approximate measure for the focal length of the pinhole. Drill a hole into the center of the body cap, and cover it by taping an appropriate pinhole to the back (fig.8). Keep the modified cap in the camera bag for quick conversions between lens and pinhole imaging.

As with lens-based images, the quality of pinhole images increases with negative size. This may be of some consequence for images that mainly require almost endless depth of field. Nonetheless, it is important to realize that the beauty of pinhole images is largely based on their diffraction-limited performance. The inherent fuzziness makes pinhole photography perfectly suited for all those images where the subject will benefit from a little softness or romantic mystery. If pinhole images were perfectly sharp, there would be little reason to make them.

## The Optimal Pinhole Diameter

Realizing that pinhole images can never be perfectly sharp has not stopped photographers from seeking to optimize the quality of pinhole images and searching


fig.8 Analog or digital SLRs are easily converted to sophisticated pinhole cameras by drilling a hole into a spare body cap and covering it with a pinhole plate.

for the optimal pinhole diameter (fig.8). The image clarity of lens-based photography is limited by lens aberrations and diffraction. Closing the aperture reduces lens aberrations significantly but slowly increases the degrading influence of diffraction. This improves the overall image sharpness up to a point, but with decreasing apertures, diffraction eventually becomes the only limiting factor of image clarity. Obviously, a lens-less pinhole does not suffer from lens aberrations, but the image clarity of pinhole photography is limited considerably by diffraction.

Simple geometric optics dictate that the optimal pinhole is as small as possible, because the smaller the hole, the smaller the fuzzy image circles are (see fig.3b), and the sharper the pinhole image will be. However, this ignores the influence of diffraction, which causes the light to spread, as it passes through the narrow aperture, and increases the size of the fuzzy image circles. Diffraction optics dictate that the pinhole is as large as possible to minimize light spreading. As a consequence, the ideal pinhole diameter is as small as possible and as large as necessary.

In 1857, Prof. Joseph Petzval was apparently the first to find a mathematical equation to determine the optimal pinhole diameter. Disagreeing with his proposal, Lord Rayleigh published a competing formula in 1891, which gave a much larger diameter, as did William Abney in 1895 with yet another equation. All three attempts were based on geometric optics, but no consensus was reached among photographers as to which was the 'true' optimal pinhole diameter. More equations, this time based mainly on empirical

fig.9 Most equations to calculate the optimal pinhole diameter (d) follow the following format:

$$d = k \cdot \sqrt{\lambda \cdot f}$$

where 'λ' is the wavelength of light, 'f' is the focal length of the pinhole, and 'k' is a constant value, typically between 1 and 2.

fig.10 The optimal pinhole diameter (d) to optimize image sharpness is derived from the Airy disc by:

$$d = 2.44 \cdot \lambda \cdot N$$

$$d = 2.44 \cdot \lambda \cdot \frac{f}{d}$$

$$d^2 = 2.44 \cdot \lambda \cdot f$$

$$d = \sqrt{2.44 \cdot \lambda \cdot f}$$

where 'λ' is the wavelength of light, 'N' is the pinhole aperture in f/stops, and 'f' is the focal length of the pinhole.

studies, followed until well into the 20th century. Many equations performed well enough to find enthusiastic followers, making it even more difficult to reach consensus on one optimal pinhole diameter. In retrospect, it seems like a twist of fate that Lord Rayleigh did not consider the research on diffraction by Sir George Airy from 1830, or his own diffraction criterion, which he published almost 20 years before offering his pinhole equation. Because, with his in-depth knowledge of diffraction and photography, he held the key to finding the ideal pinhole diameter, which everyone can agree to.

Remember that diffraction optics dictate that the pinhole is as large as possible to minimize light spreading, and that geometric optics dictate that an ideal pinhole is as small as possible to optimize image clarity. Considering the Airy disc and the Rayleigh criterion leads us to two theorems for an ideal pinhole diameter and suggests that there may be more than one right answer.

1. The smallest pinhole possible is based on the Airy disc to optimize image sharpness.

$$d = \sqrt{2.44 \cdot \lambda \cdot f}$$

2. The largest pinhole necessary satisfies the Rayleigh criterion to optimize image resolution.

$$d = \sqrt{3.66 \cdot \lambda \cdot f}$$

Both equations are derived, as in the example shown in fig.10, from either the Airy disc or the Rayleigh criterion. Infinity focus is assumed for both, which in reality means that they provide a depth of field from the hyperfocal distance to infinity. In both equations, the pinhole diameter is a function of the wavelength of light and the focal length of the pinhole, but a different numerical constant is used in each formula.

In 2004, Kjell Carlsson of the Royal Institute of Technology in Stockholm, Sweden conducted an evaluation of a variety of pinhole sizes. Unique to his approach was the fact that he stayed clear of subjectively comparing photographs. Instead, he computed MTF data for a number of different pinhole diameters and compared their MTF graphs. Fig.11 shows an example comparing the two proposed pinhole apertures. The diameter of equation (1) is derived from the Airy disc, and the diameter of equation (2) is based on the Rayleigh criterion. The comparison illustrates the

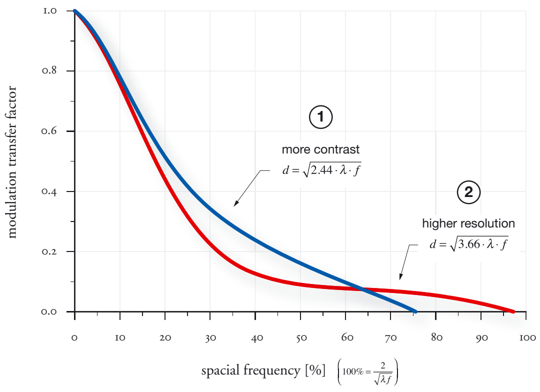
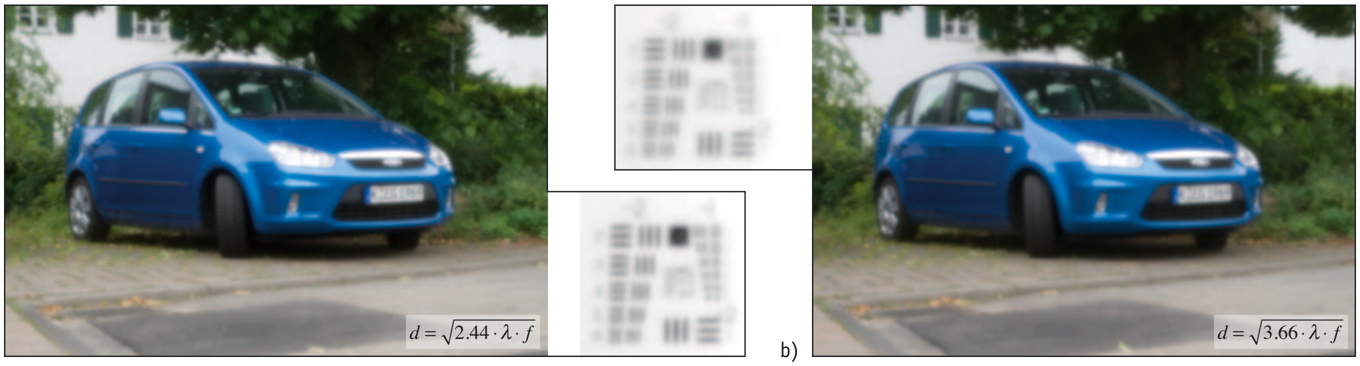



fig.11 The MTF graph compares the performance of two pinhole diameters. One offers more contrast and perceived sharpness, while the other provides more detail and resolution. (MTF data courtesy of Kjell Carlsson)

fig.12a-b (below) The test images in a) were taken with a small pinhole, based on the Airy disc, and the images in b) with a large pinhole, based on the Rayleigh criterion. The small pinhole in a) offers more contrast, while the large pinhole in b) provides more resolution. Most observers, however, perceive the high-contrast images on the left as being sharper of the two sets.

a)



performance difference of the two formulas, but it also reveals why an agreement for the optimal pinhole diameter was so difficult to achieve. Equation (1) offers more contrast and perceived sharpness, while equation (2) provides more detail and resolution.

A set of test images in fig.12 verifies the theoretical evaluation. A small-format digital SLR (see fig.8) was equipped with a small pinhole, based on the Airy disc (0.25 mm), to create the images in fig.12a, and a large pinhole, based on the Rayleigh criterion (0.30 mm), to create the images in fig.12b. The images in fig.12a have more contrast and appear to be overall sharper than the images in fig.12b, as seen in the license plates, while the images in fig.12b have more resolution, as the bar charts reveal. Confusingly, this leaves us with two options for an optimal pinhole diameter, one for contrast and one for resolution. It is necessary to decide which of the two we want to optimize, before we agree to just one optimal pinhole diameter.

The quest for the optimal pinhole diameter is generally fueled by the desire to create the sharpest pinhole image possible. Contrast and resolution are both aspects of sharpness, but as demonstrated in fig.12, human perception typically prefers high-contrast images to high-resolution images. Consequently, unless resolution is more important than perceived sharpness, my proposal for the optimal pinhole diameter (d) is based on George Airy's diffraction-limited disc:

$$d = \sqrt{2.44 \cdot \lambda \cdot f}$$

or in the more conventional format:

$$d = 1.56 \cdot \sqrt{\lambda \cdot f}$$

where 'λ' is the wavelength of light, and 'f' is the focal length of the pinhole. A common value for the wavelength of light is 555 nm (0.000555 mm), which is the eye's sensitivity peak and an appropriate value for standard pictorial photography. For infrared photography, use the film's spectral sensitivity instead.

The graph in fig.13 shows how the optimal pinhole diameter increases with focal length, and the table in fig.14 provides useful data for some popular focal lengths to help with the design, exposure and composition of pinhole images.

## Pinhole Aperture, Exposure and Focus

As we saw in fig.5a, regular sewing needles are convenient tools to create quality pinholes. Since the beginning of the 19th century, needle sizes are denoted by numbers, and the convention is that the thickness of a needle increases as its number decreases. In other words, the higher the needle size number, the thinner the needle. Fig.14 identifies the most appropriate needle size to create a popular pinhole diameter.

Fig.14 also shows the approximate pinhole aperture in f/stops with 1/3-stop accuracy. Use this aperture for all exposure calculations or measurements, and don't forget to consider film reciprocity, as exposure times are likely long enough for reciprocity to have a significant effect. Most general-purpose lightmeters do not have aperture settings beyond f/64. This makes their application somewhat cumbersome for pinhole photography, where apertures of f/256 and smaller are the norm. However, fig.14 provides exposure compensation for all f/stops in relation to f/64. Set your lightmeter to f/64 to determine the exposure, and extend the exposure time according to the indicated f/64 compensation for your pinhole aperture. You will find a special pinhole dial in the appendix under 'Tables and Templates' to simplify this task.

Most pinhole cameras do not provide any type of focus adjustment, and therefore, a pinhole camera is always focused at infinity. This means that the depth of field extends from the hyperfocal distance to infinity, and the hyperfocal distance is the front focus limit. A look at the hyperfocal distance in fig.14 demystifies why pinhole cameras are considered to have almost endless depth of field. At f/256 pinhole focus amazingly extends from 270 mm to infinity.

Depth of field can be extended even further if the pinhole camera provides some kind of a focus adjustment, as it would in a view camera conversion. Maximum depth of field is obtained when the pinhole

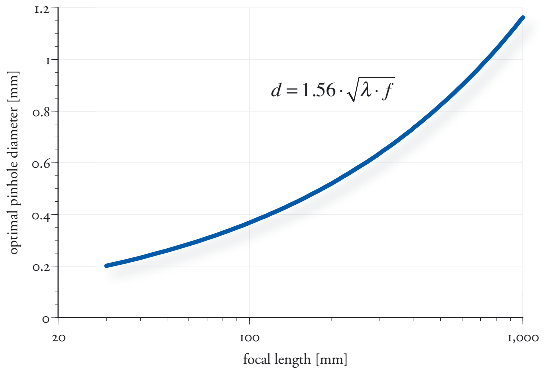



fig.13 The optimal pinhole diameter for perceived sharpness is based on the equation for the Airy disc.

| focal length [mm] | pinhole diameter [mm] | needle size | aperture | f/64 rel exp [stops] | max resolution [lp/mm] | hyperfocal distance [mm] | pinhole extension [mm] |
|---|---|---|---|---|---|---|---|
| 35 | 0.22 | - | f/128 •• | +2 •• | 9.2 | 105 | 18 |
| 45 | 0.25 | 15 | f/180 | +3 | 8.1 | 135 | 23 |
| 55 | 0.27 | 14 | f/180 • | +3 • | 7.3 | 165 | 28 |
| 75 | 0.32 | 13 | f/180 •• | +3 •• | 6.3 | 225 | 38 |
| 90 | 0.35 | 12 | f/256 | +4 | 5.7 | 270 | 45 |
| 105 | 0.38 | 11 | f/256 • | +4 • | 5.3 | 315 | 53 |
| 135 | 0.43 | 11 | f/256 •• | +4 •• | 4.7 | 405 | 68 |
| 150 | 0.45 | 10 | f/256 •• | +4 •• | 4.4 | 450 | 75 |
| 180 | 0.49 | 10 | f/360 | +5 | 4.1 | 540 | 90 |
| 210 | 0.53 | 9 | f/360 • | +5 • | 3.8 | 630 | 105 |
| 300 | 0.64 | 8 | f/360 •• | +5 •• | 3.1 | 900 | 150 |
| 450 | 0.78 | 6 | f/512 • | +6 • | 2.6 | 1,350 | 225 |
| 600 | 0.90 | 4 | f/512 •• | +6 •• | 2.2 | 1,800 | 300 |
| 800 | 1.04 | 3 | f/720 | +7 | 1.9 | 2,400 | 400 |

fig.14 This table provides useful data for some popular focal lengths to help with the design, exposure and composition of pinhole images.

a) optimal pinhole diameter
b) needle number to make pinhole
c) working aperture in 1/3 stops
d) exposure compensation relative to f/64 exposure measurement
e) maximum pinhole resolution
f) hyperfocal distance
g) pinhole extension required to focus at hyperfocal distance

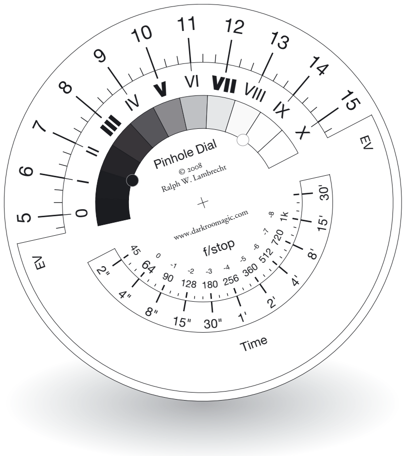



fig.15 In the chapter 'How to Build and Use a Zone Dial', a useful Zone System dial is presented for general exposures. Pinhole photographers will be happy to know that they can find a special pinhole version in the appendix under 'Tables and Templates'.

is focused at the hyperfocal distance, in which case, depth of field starts at half the hyperfocal distance and extends to infinity. Of course, visual focusing is impossible with small pinhole apertures and the dim images they create. That is why the last column in fig.14 provides a dimension for the pinhole extension. Extend the pinhole-to-film distance by this amount in order to focus the image at the hyperfocal distance. As with all close-up photography, moving the pinhole closer to the subject moves it away from the film, which reduces film illumination. This must be compensated by an increase in exposure time, and in case of the optimal pinhole diameter, by an exposure increase of 1 1/6-stop for hyperfocal focusing.

## Pinhole Alternatives

There is hardly another field in photography more inviting to experimentation than pinhole photography, and modifying the pinhole aperture is a creative method to produce endless possibilities for image alternatives. If the aim is image clarity, a plain circular hole of optimal diameter is hard to beat, but if you like to explore unconventional substitutes, try apertures of all shapes, including horizontal, vertical and wavy slots. More technical aperture alternatives for pinholes are diffraction zone plates and photon sieves.

Lenses produce images through refraction; pinholes produce images through diffraction. With zone plates and photon sieves (fig.16), photographers take full advantage of diffraction by creating apertures that simulate the Airy diffraction pattern. Both have larger apertures and require less exposure than plain pinholes but produce fuzzier images with less depth of field.

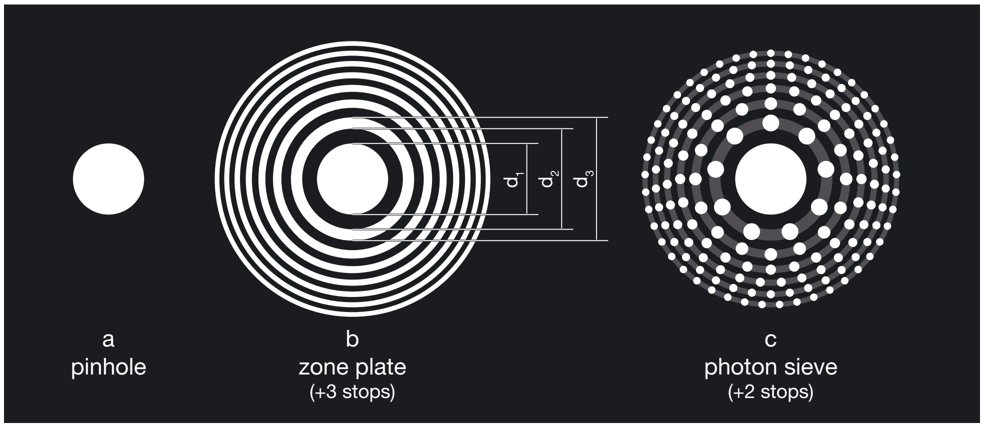



fig.16 Diffraction zone plates and photon sieves are alternatives to a plain pinhole. They have larger apertures and require less exposure but produce fuzzier images with less depth of field.

A zone plate (fig.16b) consists of a center hole, which has the same diameter as the optimal pinhole, and an arbitrary number of concentric rings or zones, alternating between opaque and transparent. The outer diameter for each zone $(d_n)$ is given by:

$$d_n = 1.56 \cdot \sqrt{\lambda \cdot f \cdot n}$$

where 'λ' is the wavelength of light, 'f' is the focal length of the pinhole, and 'n' is the sequential number of the zone. It is important to note that each zone, whether opaque or transparent, has the same surface area as the center pinhole. This means that a zone plate with seven additional transparent zones has eight times the light-gathering power of the pinhole alone, which is equivalent to an aperture improvement of +3 stops.

Another pinhole alternative is a multi-pinhole pattern, also called mega-pinhole or photon sieve. Instead of using the entire ring of a diffraction zone, as in the zone plate, an arbitrary number of small pinholes are distributed along the theoretical zones of the photon sieve, forming a hole pattern for each diffraction zone. While the diffraction zones become thinner and thinner as they ripple away from the center pinhole, the pattern holes become smaller and smaller towards the outside of the photon sieve. The design in fig.16c distributes just enough holes in each zone to equal half the surface area of the center pinhole for each hole pattern. This means that a photon sieve with six additional hole patterns has four times the light-gathering power of a single pinhole alone. This is equivalent to an aperture improvement of +2 stops.

Of course, it's impossible to cut or drill zone plates and photon sieves like pinholes. The best way to make them is to create an enlarged, tone-reversed drawing of the design and photograph it onto high-contrast B&W film thus reducing it to the right size. Two design patterns are available in the appendix under 'Tables and Templates'. The trade-off for increased light-gathering power with zone plates and photon sieves is a reduced depth of field and a loss of image quality, which is a result of larger apertures and less than perfectly transparent materials. Nevertheless, for many photographers, the unique image characteristics of these special apertures more than make up for all their disadvantages. The same is true for pinhole images in general. They are well worth a try.