Using the PMTF to Assess the Optical Performance of Various Types of Intraocular Lenses

By

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1 Introduction

The PMTF is a commercial device developed by Lambda-X Ophthalmics (Nivelles, Belgium) to measure the optical performance of intraocular lenses (IOLs). PMTF stands for Power and Modulation Transfer Function(MTF). It is an instrument with the purpose of measuring real-time MTF and the power of refractive and diffractive IOLs. The PMTF is great for both research and development purposes, as it provides insight into the mechanism of action of various structures used to enhance the capabilities of modern IOLs. Additionally, the systems can be used for production quality purposes.

The PMTF is an instrument that is used to measure MTF in accordance with the ISO11979-2 standard. The standard, titled *Ophthalmic implants — Intraocular lenses —Part 2: Optical properties and test methods* defines various tests to measure the optical performance of IOLs including dioptric power, resolution efficiency and MTF. These procedures have also been adopted by the Food and Drug Administration (FDA) to aid in defining lenses that meet the definition of a multifocal and/or extended depth of field (EDOF) lens. The system measures the power of the IOL using the principle of measuring the magnification of the image of a known target. This procedure has been suggested by the ISO11979-2 standard, and the PMTF has built in targets of a standardized circle and a grid pattern for this purpose. Furthermore, the PMTF has a 1951 USAF target for assessing the resolution efficiency. Finally, the device uses tilted horizontal and vertical edge targets to measure MTF. Overall, the PMTF is an instrument with a unique configuration and dedicated software, which makes it extraordinarily suitable for inspecting and characterizing both standard IOLs and more advanced designs such as multifocal and EDOF IOLs, in both research & development, and production environments.

1.1 Optical Layout

The PMTF's optical layout is shown in Figure 1.

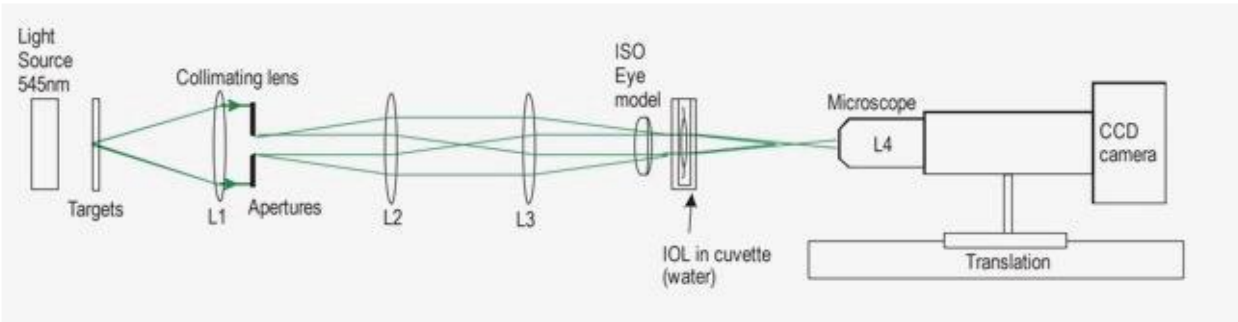


Figure 1: PMTF Optical Layout

The standard light source is emitting at 545 nm and a FWHM value of 22 nm, essentially matching the peak photopic response of the eye. There is also an optional multisource plugin, where the standard 545 nm light source is replaced with 3 light sources emitting at:

- 480 nm (FWHM: 10 nm)
- 550 nm (FWHM: 10 nm)
- 650 nm (FWHM: 10 nm)

The source is used to illuminate various built-in targets. The target is placed at the front focal plane of the lens L1 so that collimated light is emerging. The light passes through an afocal relay (lenses L2 and L3) and enters an artificial eye model. The eye model consists of an artificial cornea, and a saline-filled wet cell into which the IOL under test is mounted. The eye model forms an image of the target. This image, in turn, is viewed with a microscope objective (L4) and a CCD camera mounted on a motorized translation stage. There are five different targets that are incorporated into the standard instrument. In the PMTF software, these targets can be selected on the Adjust tab. Figure 2 shows the location of this setting within the PMTF software. The target options are:

1. Circle/Grid for power measurement
2. Horizontal edge for Sagittal MTF measurement
3. Vertical edge for Tangential MTF measurement
4. Siemens target for alignment and quality evaluation
5. USAF target for quality evaluation and resolution measurement

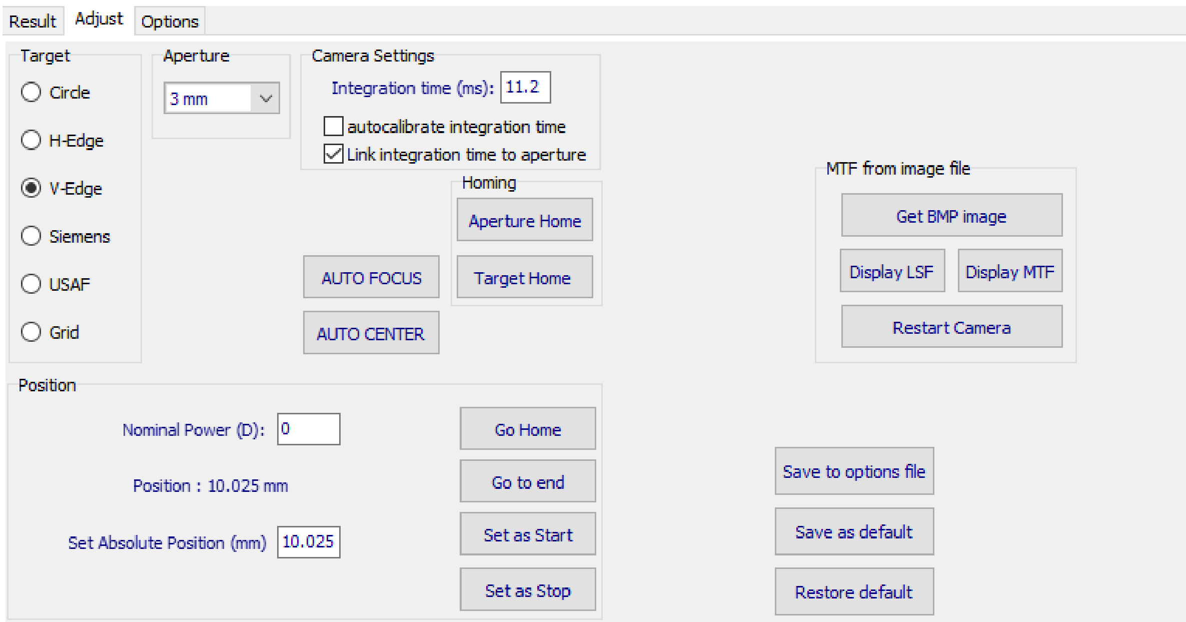


Figure 2: Target Selection

Note: Each target will be used in the ensuing analysis.

In addition to the target system, the PMTF optical train also contains various apertures. The apertures are located immediately behind L1 and is relayed by lenses L2 and L3 to the IOL plane. In this manner, analyses can be carried out for various sized pupils. There are four different apertures accessible through the PMTF: 2 mm, 3 mm, 3.75 mm, and 4.5 mm. The different aperture sizes can be selected in both the Results and the Adjust tabs in the PMTF software. Figure 3 shows the location of the aperture size options within the Results tab.

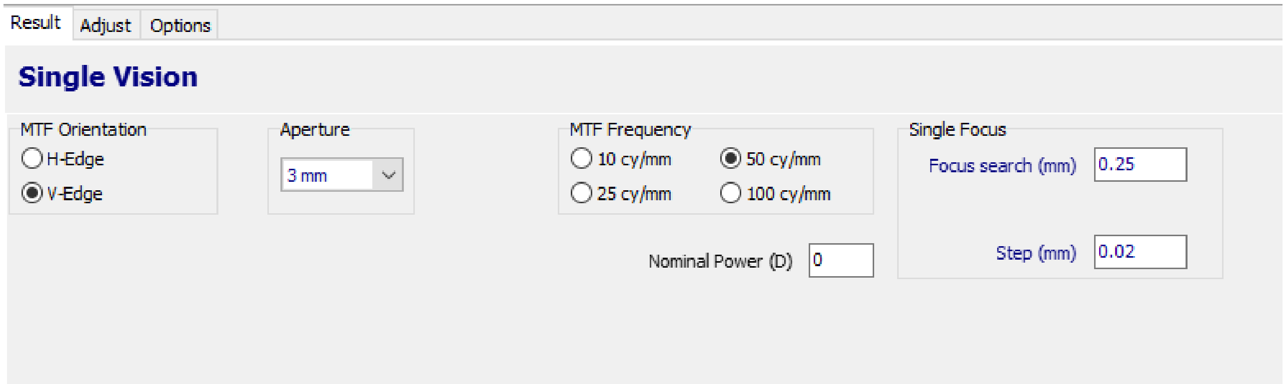


Figure 3: Aperture Selection

There are two different eye models available for the PMTF system, labeled ISO-1 and ME-3. These models follow the suggested model eyes outlined in the ISO 11979-2 standard. The standard gives specs for Model Eye 1 and Model Eye 2, but also states that equivalent systems can be used. T Below, the differences between the two models are illustrated in Figures 4 - 7. Figure 4 shows the Model Eye 1 without an IOL in place. The model consists of an achromatic doublet that is well corrected for spherical aberration, and a quartz wet cell filled with saline. An aperture is placed at the location of the IOL. Figure 5 shows the Model Eye 1 with the IOL implanted behind the aperture. In the PMTF implementation, the ISO-1 model is equivalent to the Model Eye 1 of the standard. A spherical aberration free doublet and wet cell are used in the ISO-1 model, and the aperture is relayed to the IOL plane via lenses L2 and L3 described previously. Historically, the Model Eye 1 was used when IOL surfaces were strictly spherical and the inherent spherical aberration of the IOL was always positive. By using a spherical aberration free cornea in the model, the overall spherical aberration of the model eye was dictated by the design of the IOL.

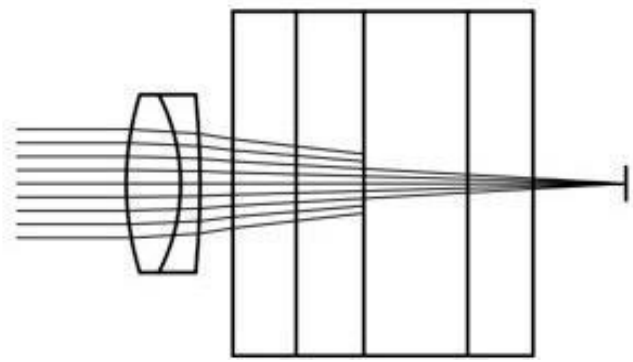


Figure 4: Model Eye 1 without IOL

Note: This model follows the descriptions of a model eye and its requirements.

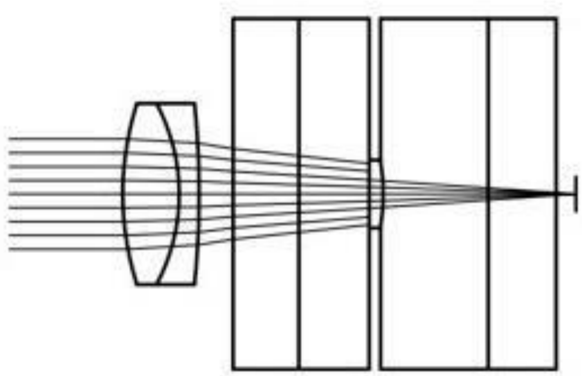


Figure 5: Model Eye 1 With a 20D Spherical IOL in Place

Note: The image plane is now closer to the last window, but it still remains outside the wet cell.

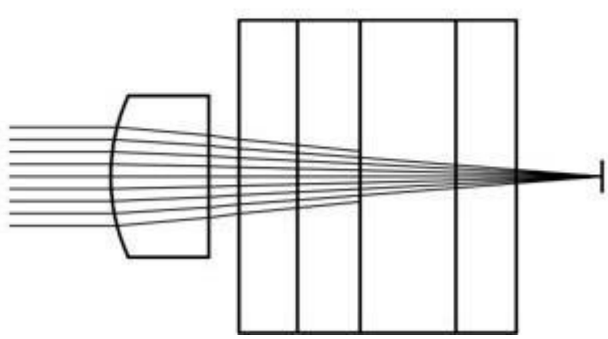


Figure 6: Model Eye 2 without IOL

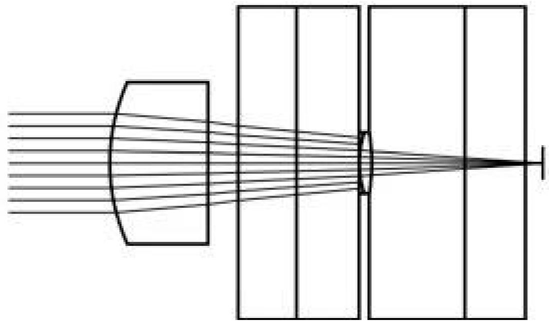


Figure 7: Model Eye 2 with Aspheric IOL that Corrects Aberration of the Model Cornea in Place

Note: The central 3 mm of the IOL are exposed. Additionally, the image plane is now closer to the last window, but still remains behind it. Similar to the model from Model Eye 1.

Figure 6 and 7 illustrate the Model Eye 2 from the ISO standard. In this model, the cornea is replaced with an aspheric surface that can be used to introduce clinically found levels of corneal spherical aberration. Most modern IOLs are designed with at least one aspheric surface, which enables the lens design is compensate for some level of corneal spherical aberration. For the ME-3 model of the PMTF, the spherical aberration of the model cornea is +0.215 microns over a 6 mm aperture.

following the eye model, a microscope objective (L4) is mounted on the translation stage. When the instrument first starts up, the microscope will focus on the eye model's focus, with a cuvette filled with saline only. When all of the positions are expressed in millimeters, the position of 0 should correspond to where the microscope is at home position furthest from the cuvette. Positive positions are achieved when the microscope is moved further from the cuvette. The PMTF also allows conversion of the distance scale to units of diopters. When the positions are expressed in diopter, higher values correspond to the microscope when moved closer to the cuvette. The lowest translation step is 2.5 µm. Units of diopters may be advantageous since IOLs are described by their power, and multifocal lenses further give an “add” power which describes the increase in lens power at its various focal planes.

To summarize, fixed apertures are relayed to the IOL plane to set the pupil size. The target appears at infinity since it is located at the focal point of L1. The eye model forms an intermediate image of the target just outside of the wet cell. The microscope is moved to image the intermediate target image onto a CCD array. Each IOL will have a different microscope position based on the IOL’s power. Lastly, the camera provides images of 1040X1040 pixels which are further processed to extract dioptric power, resolution efficiency and MTF.

1.2 MTF Measurement

MTF measurement is an important tool for understanding the performance of a lens. It is used throughout the results section of this paper to examine the performance of two types of IOLs, with both static MTF, as well as through-focus MTF.

The MTF curve is an information-dense metric that shows how a lens reproduces contrast as a function of spatial frequency. In other words, these curves offer a view of how the aberrations affect performance by illustrating the degradation in contrast of a given spatial frequency caused by the lens.

The PMTF calculates the MTF measurement by imaging an edge target, nominally vertical or horizontal, and processing the image. Figure 8 shows and example target with a slight tilt introduced to enhance the sampling of the edge blur. The sharpness of the edge within the image is dependent upon the quality of the eye (made up of the synthetic cornea or the model eye and the IOL). Note that the horizontal edge will give the sagittal MTF and the vertical edge will give the tangential MTF. Figure 9 shows the edge image of a vertical edge target while

Figure 10 shows the “Tangential MTF Live,” resulting from the vertical edge target.

The PMTF measures the MTF indirectly by processing the Edge Spread Function (ESF) from the blurred edge image. Referring to Figure 8, the software automatically constructs the ESF by projecting the 2-D image intensity values onto a 1-D representation. The magnitude of the z-axis is the shortest distance from a pixel at the x-y coordinates to the slanted edge. The ISO based approach states that for each pixel, the z value is calculated as shown in equation 1.

$$z = \left[x - e(y)\right] \cdot \cos(\theta)$$

Equation 1: ESF Z Value Equation

e(y): location of edge in row y

Θ: relative edge angle

Once the ESF has been resampled, the MTF can be determined. The first step is to calculate the Line Spread Function (LSF), which is the numerical derivative of the sampled ESF. Next, the MTF is calculated as the magnitude of the Fast Fourier Transform of the LSF, normalized to unity by the zero-frequency component.

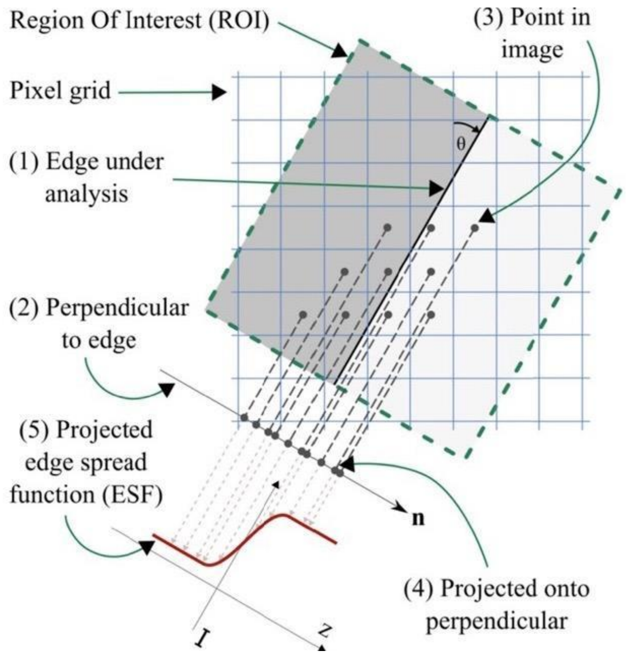


Figure 8: Example of Edge Blur Sampling and Projection Down to the ESF.

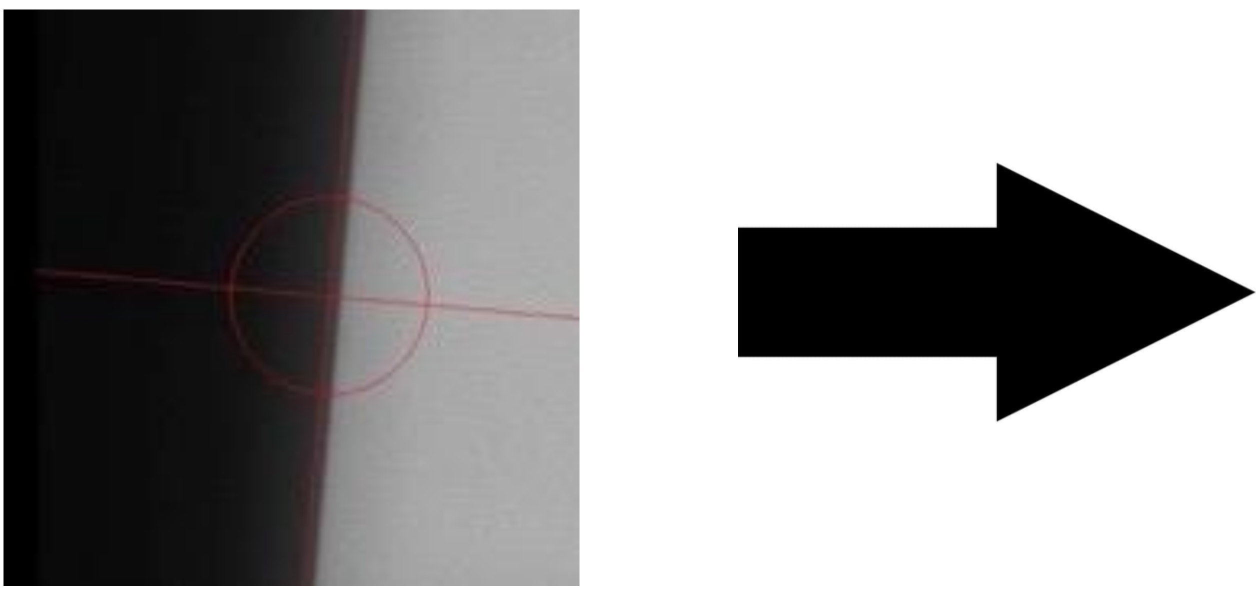


Figure 9: Vertical Edge Target

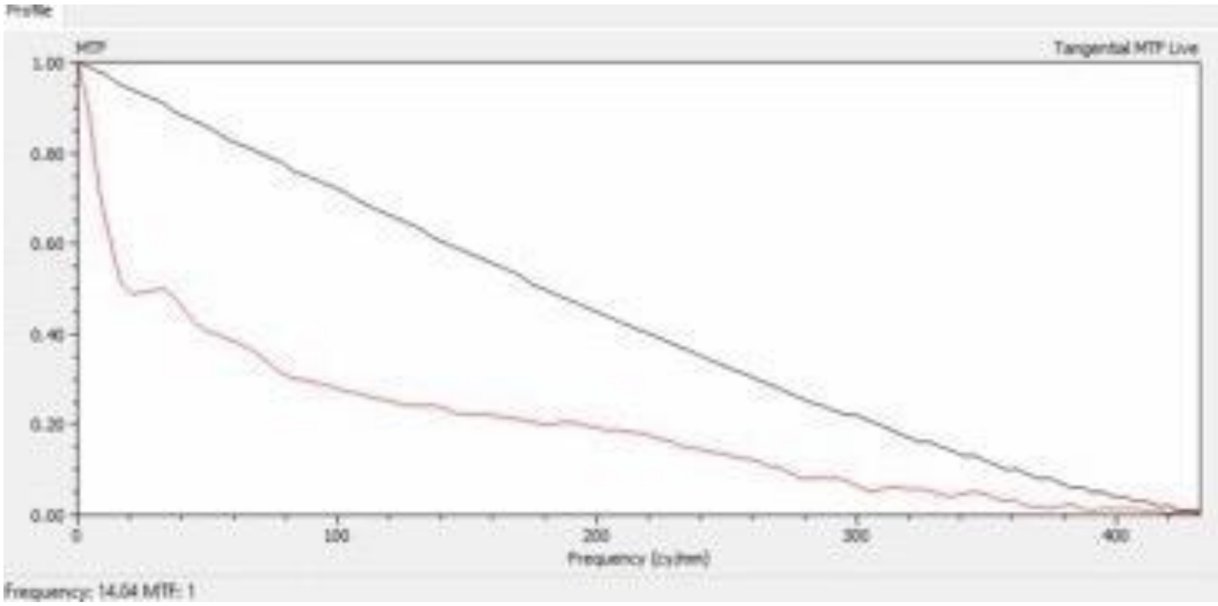


Figure 10: Tangential MTF Live

Note: The frequencies were calculated for discrete values that depend on the edge image size and the resolution. The eye can only resolve frequencies up to the range of 100-150 cy/mm, depending on the individual.

Figure 10 is an example of the MTF as a function of spatial frequency, which is typically captured for the image plane. Alternatively, through-focus MTFs are often useful for analyzing the performance of multifocal and extended depth of focus IOLs. In this case, the spatial frequency is fixed (typically 50 cyc/mm is used for ocular cases), and the location of the image plane is shifted to multiple locations on either side of best focus. Figure 11 illustrates a through-focus MTF plot for a Trifocal IOL at 50 cyc/mm. Note, the three distinct peaks in the MTF values which correspond to the foci of the Trifocal. Additionally, note how the peaks are sharper for the larger aperture since the size of the foci is inversely proportional to aperture size.

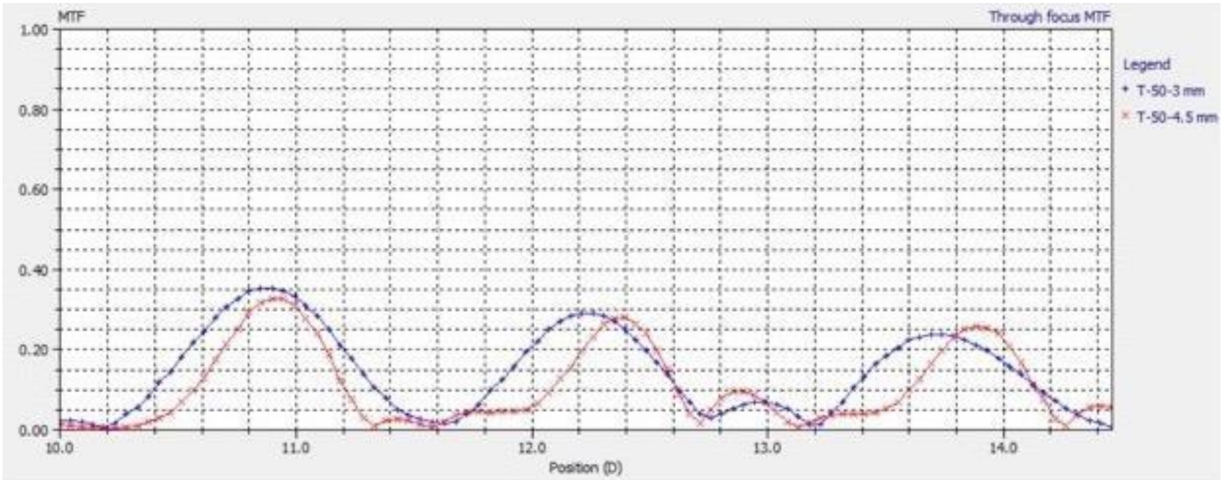


Figure 11: Typical Through Focus MTF Curves for a Trifocal IOL at Apertures of 3 mm and 4.5 mm.

2 PMTF Startup

2.1 PMTF Warm-Up

After powering up the PMTF by flipping the switch on the rear of the unit, Lambda-X recommends the user to wait between 10 to 15 minutes before starting to measure data. This is recommended because it allows for sufficient thermal stabilization of the instrument. There is no danger in using the PMTF as soon as it is turned on. However, small differences in the measured values may exist prior to the thermal stabilization process. Make sure to always turn the PMTF off if it is not being used.

2.2 Model Eye Installation

The table in which the model eye is located must be installed at all times as long as the user is not switching out components of the table. This will help prevent any damage or misalignment that may happen with time.

To install the model eye, follow the steps below:

1 - On the left side of the table, make sure that the knob is loose enough to allow the pins located on the X-Y table to be placed within the holes easily.

2 - The three pins on the X-Y table should now be inserted in the corresponding 3 holes located on the stage. This is shown in Figure 12.

Figure 12: Eye Model Installation - Step 2 Insert the Three Pins on the X-Y Stage into the Holes on the PMTF Stage.

3 - Push the X-Y table all the way in until it sits perfectly against the stage. Then turn the left knob until the eye model is firmly tightened within the system, as shown in Figure 13.

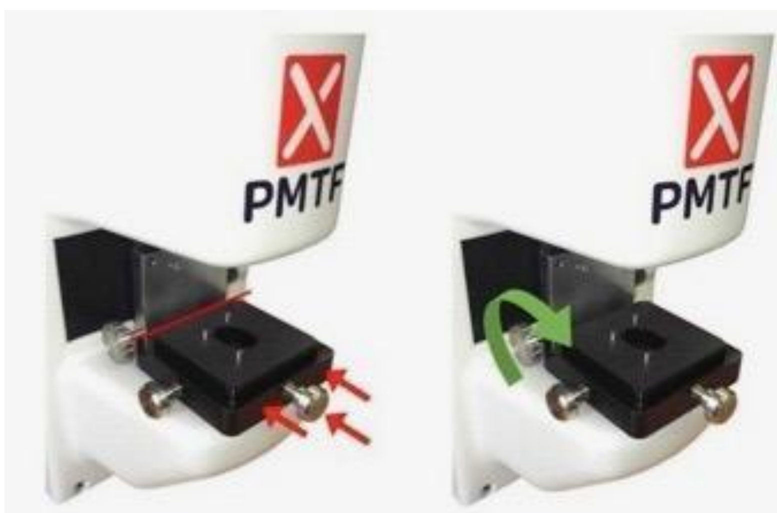


Figure 13: Eye Model Installation - Step 3 Tighten Knob to Securely Fasten the X-Y Stage.

The process is reversed to remove a given X-Y stage.

2.3 Launching PMTF

One the connected computer, launch the measurement software by clicking on the PMTF icon located on the desktop. The PMTF icon can be seen in Figure 14.

Figure 14: PMTF Icon

When the software is launched, which may take a couple of minutes, the following window should appear (Figure 15). The cuvette containing only saline should now be placed onto the X-Y table. The live image displayed on the left of the startup window may initially not show an image of the target. In this case, the X-Y stage and the focus of the system need to be adjusted to bring the target into focus.

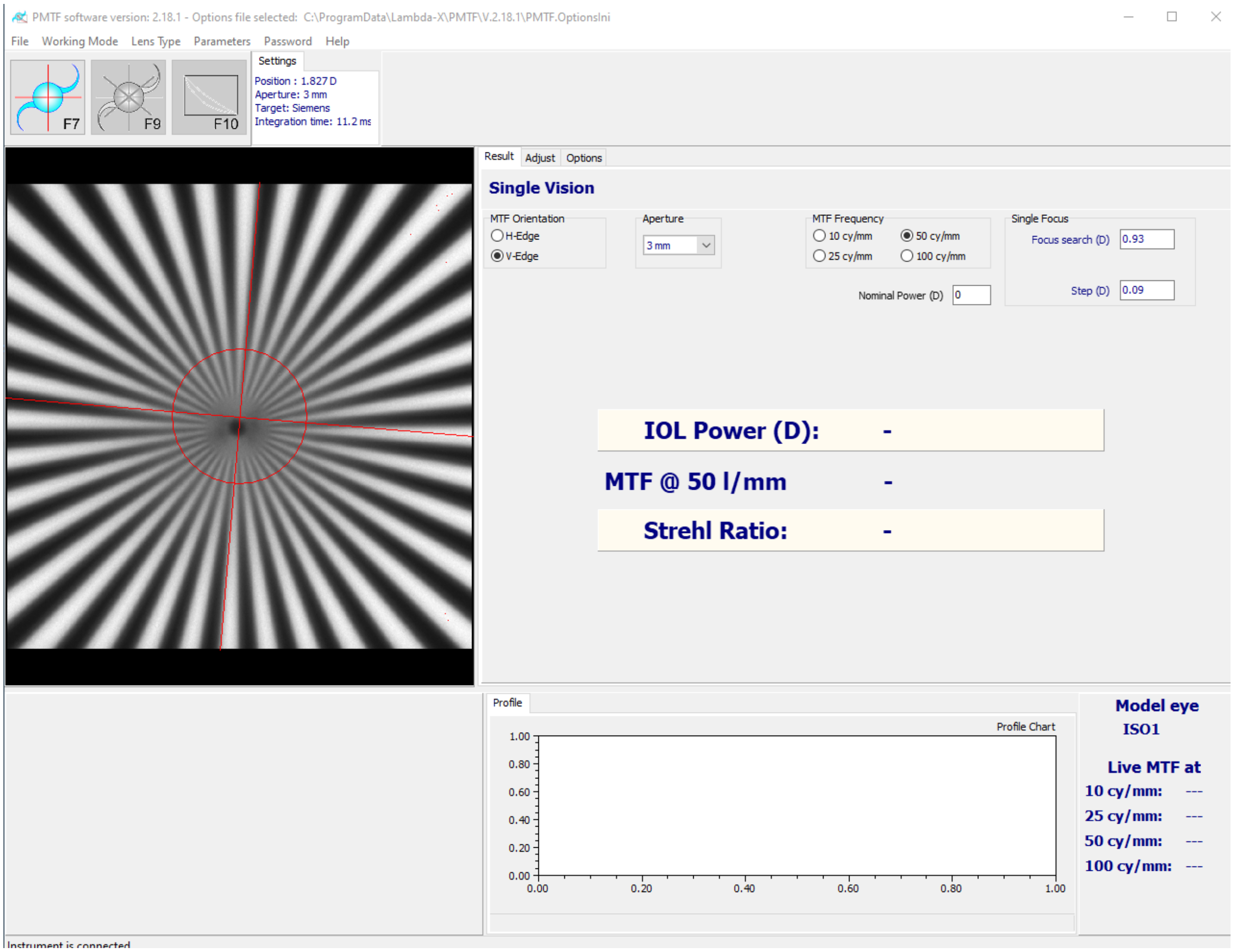


Figure 15: PMTF Software Main Window

To make the process easier, go into the Adjust tab and select the “Siemens” target. The Siemens alternating black and white spoke image will be displayed in the live video image. This is the image of the target being formed by the ISO synthetic cornea. The position of the X-Y table is adjusted to center this image, while the knob at the right of the stage is used to bring the target into focus. When at focus, the user should notice that the center of the Siemens is inside the red circle.

A Siemens star is a target that is helpful in determining the resolution and contrast properties of optical instruments. It is a pattern of bright spokes with a black/dark background which radiate from the center and become wider on the edge. Locally, the pattern can be thought of as a square-wave target of varying orientation and spatial frequency. Spatial frequency is low at the edge of the target and increases towards the center of the target. The orientation of the lpcal pattern rotates from vertical at the 12 o'clock position, to horizontal at the 3 o'clock position and then back to vertical at the 6 o'clock position, and so on. This means that the contrast reduction caused by the system on a square wave can be rapidly assessed at multiple spatial frequencies and orientations.

2.4 Inserting the IOL

Measurement while using the PMTF must be tested with the IOL immersed in liquid. It is strongly recommended that it should always be done with saline if possible. The PMTF system includes IOL inserts to provide a correct and reproducible positioning of the IOL with reference to the synthetic cornea.

The first step is to place the IOL into the Lambda-X insert as shown in Figure 16. Each IOL has a set of haptics (arms) that are wedged into the circular opening of the insert. These haptics provide spring force to center the lens within the insert, and maintain its position. The insert is then placed in an aluminum plate, and then the entire assembly is inserted into a glass cuvette.

Finally, the cuvette is placed onto the X-Y table as shown in Figure 17. There are three alignment pins on the X-Y table that position the cuvette in a way that the IOL is centered over the synthetic cornea. The cuvette is also filled with saline to immerse the IOL. Surface tension is able to keep the fluid in the cuvette even when placed on the stage.

Figure 16: IOL in Insert

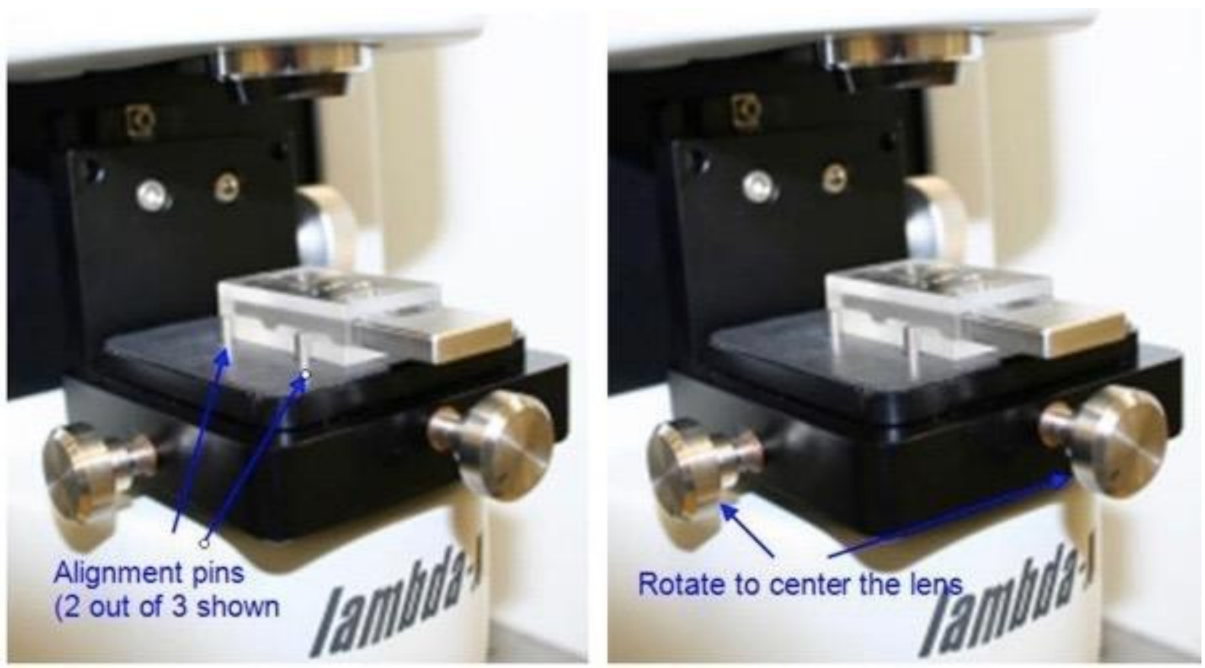


Figure 17: Cuvette on the X-Y Table & Aligned with the Knobs

Once the IOL is placed within the PMTF system, the user translates the X-Y table till the Siemens target is centered on the live image. The user should now move the microscope, on the knob on the right side of the PMTF, until the Siemens target is in the sharpest focus.

Once all steps are completed, the software screen should look like Figure 18 and the system is ready for measurements.

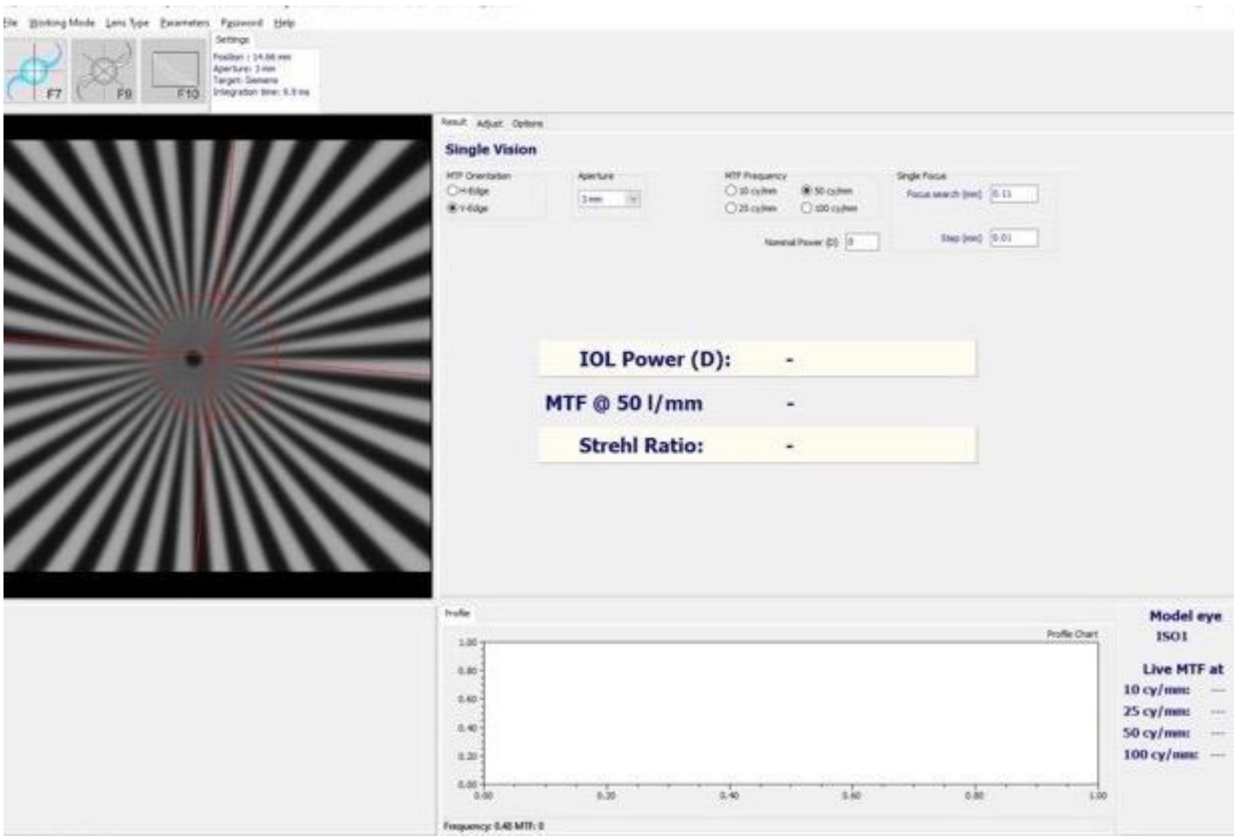


Figure 18: IOL is Ready for Testing

3 Testing

3.1 ISO11979-2 Introduction

ISO stands for the International Organization for Standardization. ISO is a worldwide federation of standards that are held nationally. The ISO technical committees are responsible for preparing the International Standards. ISO works closely with International Electrotechnical Commission (IEC) on matters that are related to electrotechnical standardization.

ISO 11979 consists of 10 different parts that give information about different topics. The parts are described below:

- Part 1: Vocab
- Part 2: Optical Properties and Test Methods
- Part 3: Mechanical Properties and Test Methods
- Part 4: Labeling and Information
- Part 5: Biocompatibility
- Part 6: Shelf-life and Transport Stability Testing
- Part 7: Clinical Investigations
- Part 8: Fundamental Requirements
- Part 9: Multifocal Intraocular Lenses
- Part 10: Phakic Intraocular Lenses

Initially, part 2 of the ISO 11979 only addressed Monofocal IOLs. However, this part has been revised to also include the requirements and testing methods for spherical Monofocal, aspheric Monofocal, toric, multifocal, and accommodative IOLs. This part of the ISO 11979 is full with several testing methods in which associated requirements are given, and one test method in which no requirement is formulated.

An important thing to pay close attention to is that for original spherical Monofocal IOLs, extensive interlaboratory testing was done before coming up with the limits specified. However, during the testing, there were some basic problems that were encountered as described in one of the other ISO11979-2 parts. The accuracy in determining the dioptric power has an issue that is not negligible in relation to the half dioptre steps in which IOLs are labeled.

3.2 Testing

There are four ISO testing methods that were tested in this paper. The first procedure was to test the through-focus USAF target. The second procedure was to test the through-focus MTF at 50 cyc/mm. The third procedure was to test the MTF with tilt. Lastly, the fourth procedure was to test the MTF with decentration. All of these testing procedures was tested with model eye 1.

There are two different types of IOLs that are reported during this paper: Alcon's TFAT00 IOL and a Monofocal IOL. It is important to understand what kind of IOL is being tested. Therefore, there will be a brief explanation of how to read Alcon IOL with a few examples.

In Figure 19, there is an image of Alcon's TFAT00 IOL. This is the IOL that will be tested throughout this research. Therefore, it is very important that the user understands how to read it.

Figure 19: Alcon TFAT00

Reading TFAT00

TF - This states that the IOL is Trifocal. Trifocal lenses are a newer type of lens which allow for three ranges of clear vision.

A - This states that the IOL is aspheric rather than spherical. The difference in the shape between the two can be seen in Figure 20. Aspheric lenses have some key advantages such as their ability to fix aberrations for clear vision, less eye-magnification, and their smaller size.

T00 - Which means that this IOL is not toric.

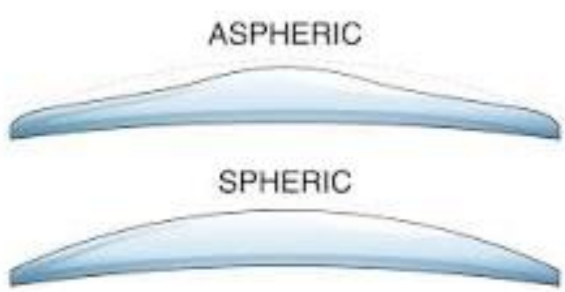


Figure 20: Aspherical vs Spherical

Figure 21 is an image of Alcon's SN60D3. This IOL will not be reported at any time during this paper and is only shown to explain how to read Alcon's IOLs.

Figure 21: Alcon SN6D2

Reading SN60D3

S - Single piece. This means that the whole IOL is one piece and that it is composed of the same material (acrylic, silicone, or PMMA). An example of this IOL can be seen in Figure 22.

N - Natural, meaning it is not clear and blocks off blue light

60 - This means that the IOL is spherical rather than aspherical. Some advantages of spherical IOLs is that they tend to be cheaper and they require less coatings (anti- scratch and anti-glare) to prevent reflections from their flatter lens surface.

D3 - This means that there is an X power “w/4.0.”

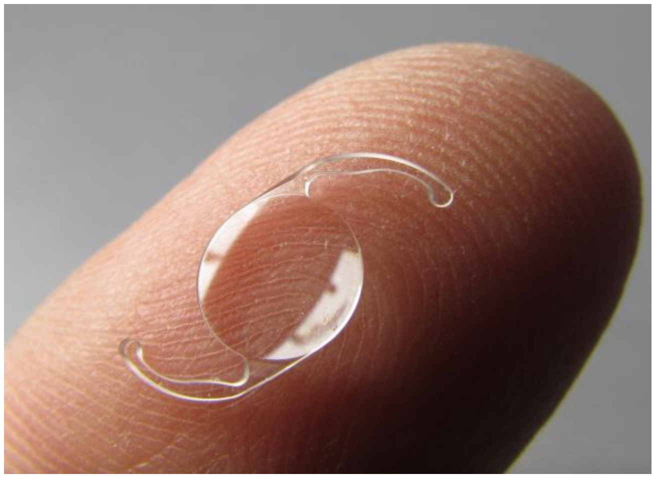


Figure 22: Single Piece IOL

Figure 23 is an image of Alcon's SN6AD2. Again, this IOL will not be reported at any time during this paper and is only shown to explain how to read Alcon's IOLs.

Figure 23: Alcon's SN6AD2

Reading SN6AD2

S - Single Piece

N - Natural, meaning it is not clear and blocks off blue light

6A - Aspherical

D2 - There is an add power "+2.5."

The last lens reported on this paper is a Monofocal IOL. It is an IOL with a fixed focus for one distance, meaning that Monofocal IOLs can only be for near focus, mid-distance focus, or distant focus. The IOL will be made for one of these focuses and can never be changed.

3.2.1 Through-Focus USAF Target

3.2.1.1 Introduction

Test targets are used to help determine the performance of an imagining system. “This includes troubleshooting a system; benchmarking, certifying, or evaluating measurements; or establishing a foundation to ensure multiple systems work well with one another” (Edmund Optics).

The USAF target is a very common test target method and consists of vertical and horizontal lines, these are known as elements of different sizes (Figure 24).

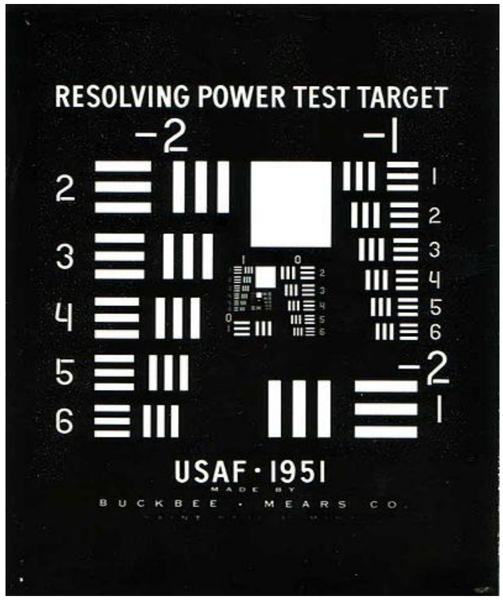


Figure 24: USAF Example

These elements, horizontal and vertical lines, are used by this system to simultaneously test the vertical and horizontal resolutions at discrete spatial frequencies (line pair per millimeter) in the object plane. The vertical bars are used to calculate horizontal resolutions and the horizontal bars are used to calculate the vertical resolutions.

An overview of the USAF target is that they are designed so that higher resolution elements are closer to the center of the target. The lower resolution elements will be closer to the target edges. This placement is helpful for testing zoom lenses because it allows for the higher resolution elements to remain in the FOV as the magnification decreases the FOV.

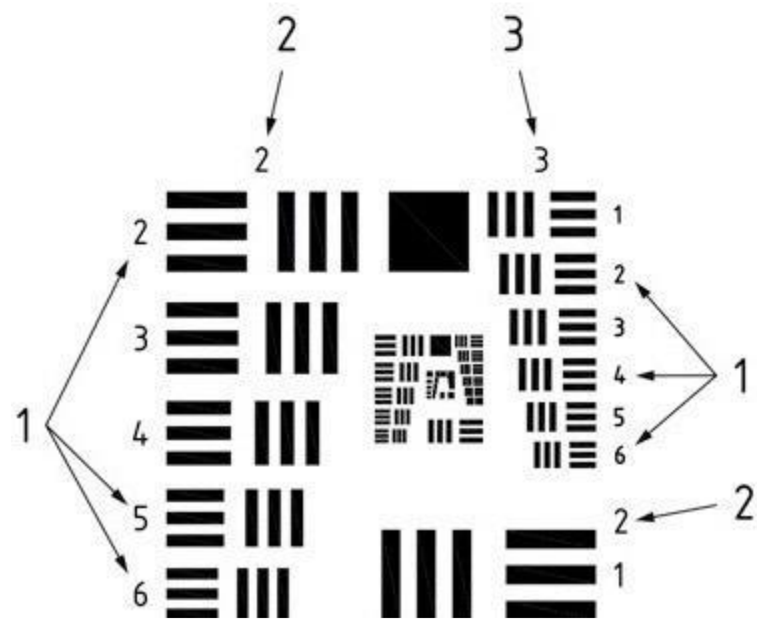


Figure 25: USAF Target with Group 0 and 1 Omitted

Key

1 Element number

2 Group 2

3 Group 3

3.2.1.2 Set-Up

Setting up the PMTF to test the USAF target first requires the user to complete the PMTF startup explained in part 3. Once the PMTF startup has been completed, the user can start the following steps. It is recommended to do this procedure in diopter.

Multifocal lenses will have multiple Siemen Star focus points at different eye model distances, as expected. For setting up the USAF target test, the user will want to focus the near vision Siemen Star, the star closest to the microscope. This will allow the PMTF to determine all of the points.

On the top of the software, there should be an option that allows the user to change the lens type by clicking on “Lens Type.” The following options can be selected:

1. Single Vision
2. Through focus
3. Multifocal
4. ISO11979 - Through Focus
5. ISO11979-9 Multifocal

For this part, the user should click “ISO11979 - Through focus.”

Once the system is in through Focus, the user should now click on the adjust tab and click on the “USAF” option (Figure 26). Once the following is completed, the user should now be able to see the USAF target on the live image (Figure 27).

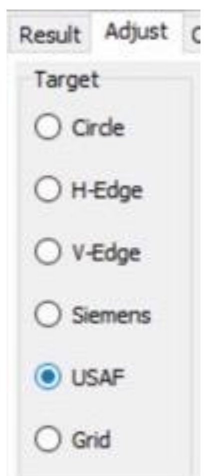


Figure 26: Targets Available in “Adjust” Tab

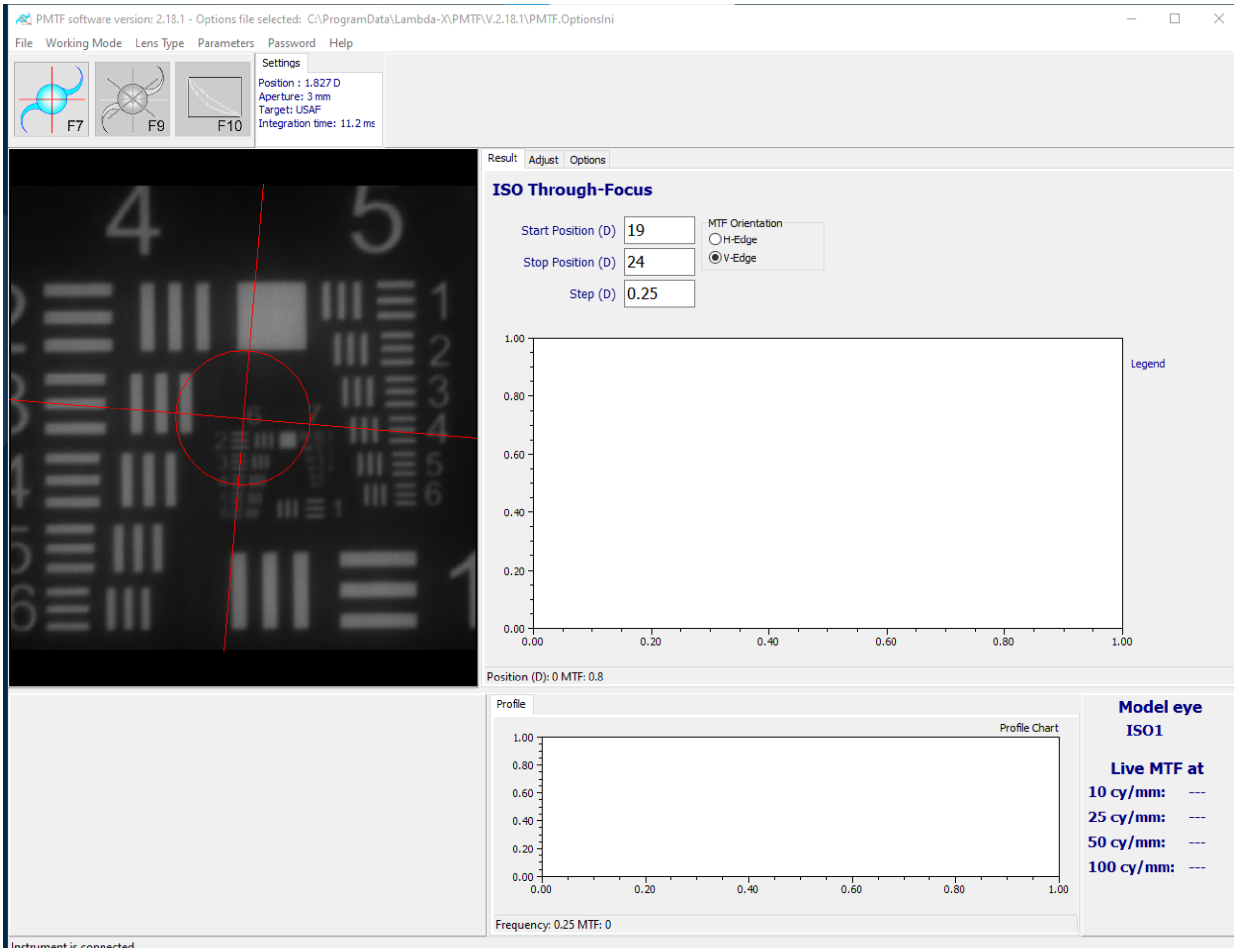


Figure 27: USAF Target Software Screen

Note: The start and stop position are determined by the lens's power. This picture was taken for a Trifocal 20D lens, meaning that we would expect a first peak around 20D and then two following peaks.

A reminder that the USAF target testing is a method that is proposed by the ISO11979-2 for evaluating the resolution efficiency for a lens. A user can quickly bring the USAF target into position by pressing Ctrl+F5 or as explained previously.

3.2.1.3 Results

The results for the following tests can be seen below. Alcon's TFAT00 IOL USAF target can be seen in Figure 28 and the Monofocal IOL USAF target can be seen in Figure 29.

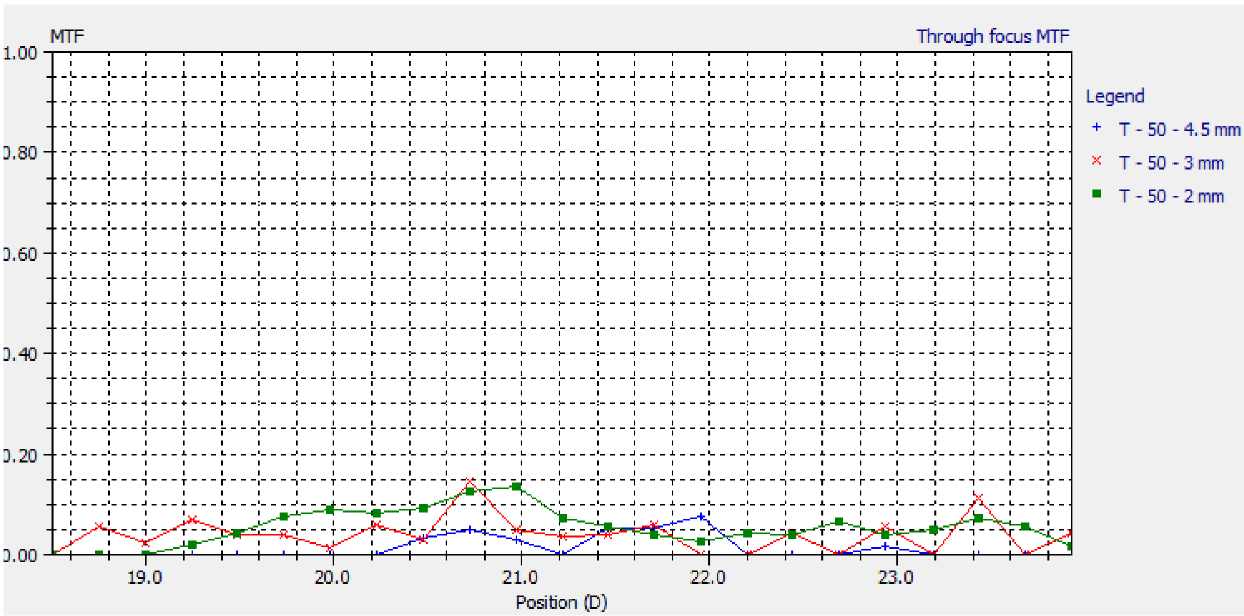


Figure 28: Alcon's TFAT00 USAF Target

For the Trifocal lens, we can see three MTF peaks for the USAF target. This is expected since the Trifocal lens should have three points of focus. The first MTF peak is around 20.8D, the second is around 21.5D and the third, last one, is around 23D.

Note: For easier to read MTF peaks, the user can lower the step value. This will allow the computer to read more points and have a smoother graph.

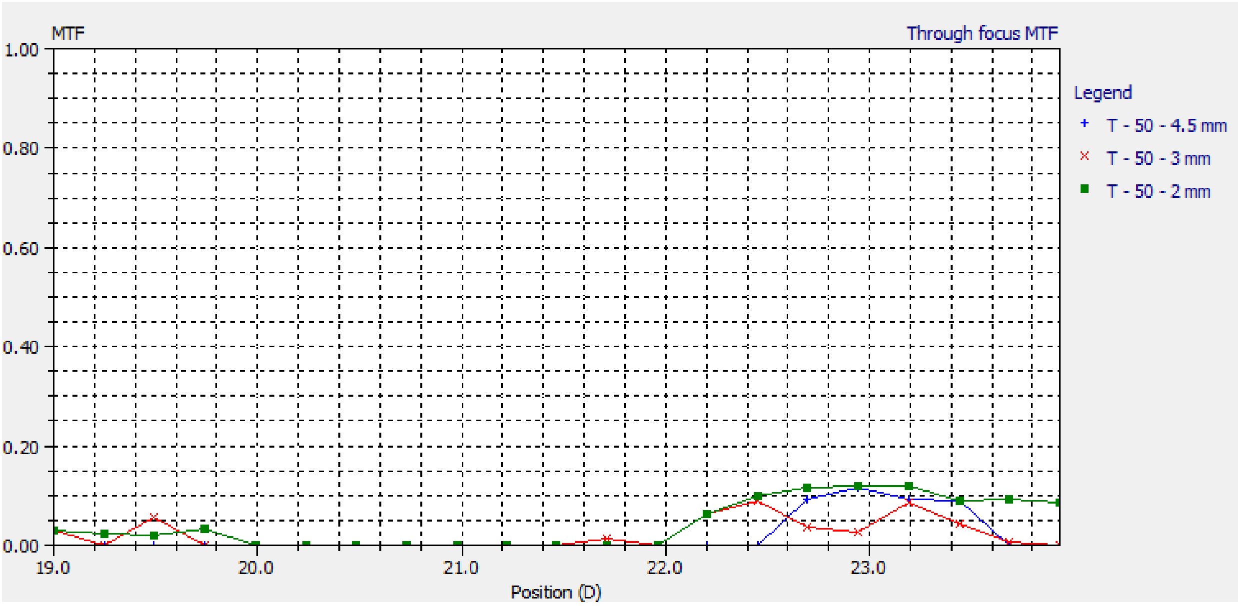


Figure 29: Monofocal USAF Target

The Monofocal has one MTF peak as expected. The peak is at the 22.8D range.

3.2.2 Through-Focus MTF

3.2.2.1 Introduction

The through focus lens type must be used to measure a through-focus MTF at a given Aperture diameters and frequency. This lens type can also be chosen to determine the power range for a lens.

ISO states that the through-focus MTF's greatest purpose is that it will confirm that the actual performance of the lens is similar to its predetermined theoretical performance.

3.2.2.2 Set-up

Setting up the PMTF to test the through-focus MTF first requires the user to complete the PMTF startup explained in part 3. Once the PMTF startup has been completed, the user can start on the proceeding steps.

The user should first change the “Lens Type” to through focus. Once this is completed, the software should look similar to the one shown in Figure 30. Before making any measurement, the configuration of the testing must be defined. The options to pick from are Scanning start and stop positions, Step, MTF Orientation, Aperture, and MTF Frequency.

Figure 30: Through-Focus Home Screen

Note: The configurations determined were the configurations that originated from ISO11979 optical properties and test methods.

ISO states that any of the PMTF apertures may be used for this procedure. The two aperture/pupil sizes chosen for this report were 3 mm and 5 mm. This can be edited from the “Aperture” shown in Figure 33.

Focus to maximum MTF at 50 cy/mm for an object at infinity. This can be changed on the right side of Figure 23, under “MTF Frequency.”

The step used during this experiment was 0.5D.

Since the magnification location is at 10.025, the start position of the experiments was at 10 and the stop position was a value under 20.

Note: If the user chooses a stop position that is too large an error will pop up. This error is informing the user that the cuvette is too close to the magnification. If these errors pop up, the user must restart the software.

Once the configuration has been set-up, the user may start the measurements by clicking on Figure 31.

Figure 31: Start Measurements

Once the software is done calculating measurements, the software screen should look similar to Figure 32.

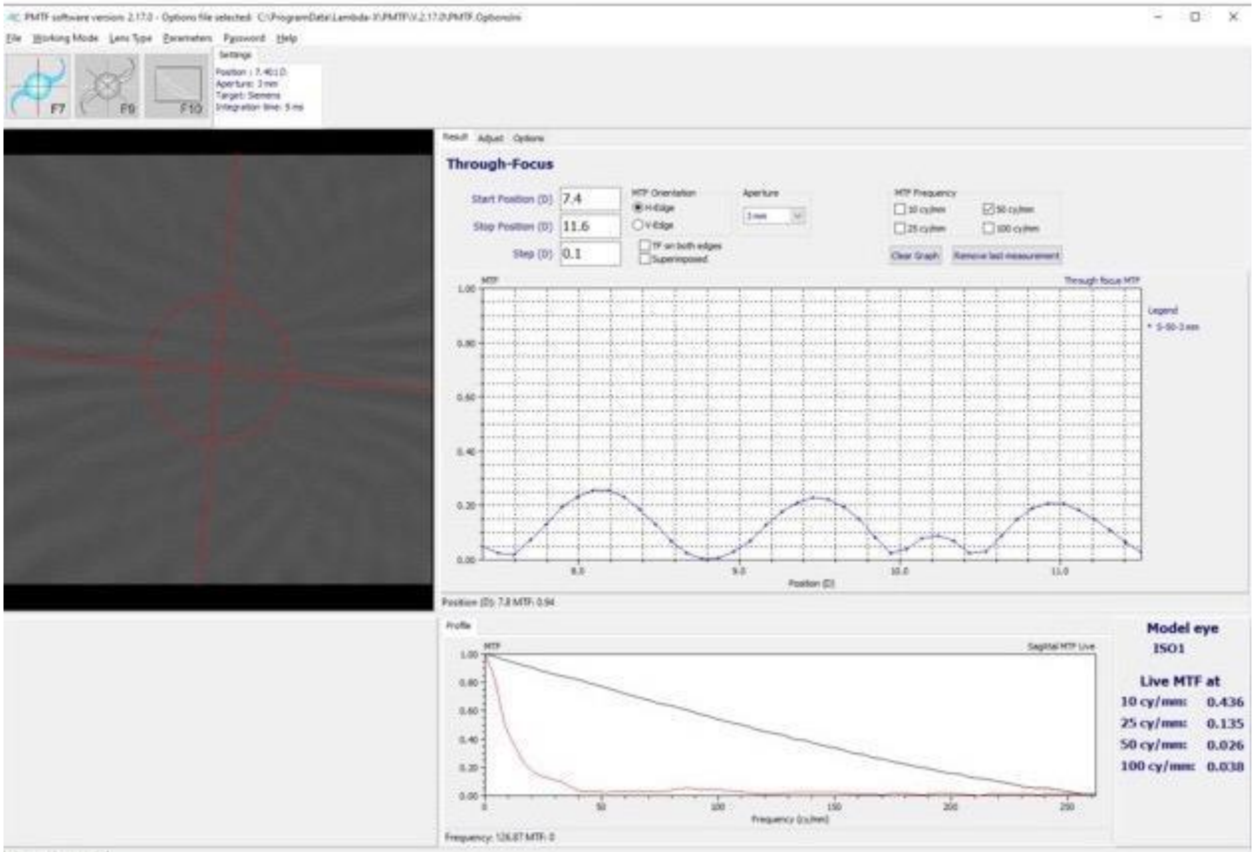


Figure 32: Typical Through-Focus Curve Screen after Measurements

Note: Through-focus measurements collect a large amount of data since it is collecting all of the frequencies for all focus planes that were measured. This large amount of information can be stored by right clicking on the graph (Figure 33).

Figure 33: Saving Through-Focus Measurements

3.2.2.3 Results

Alcon TFAT00

3mm Pupil

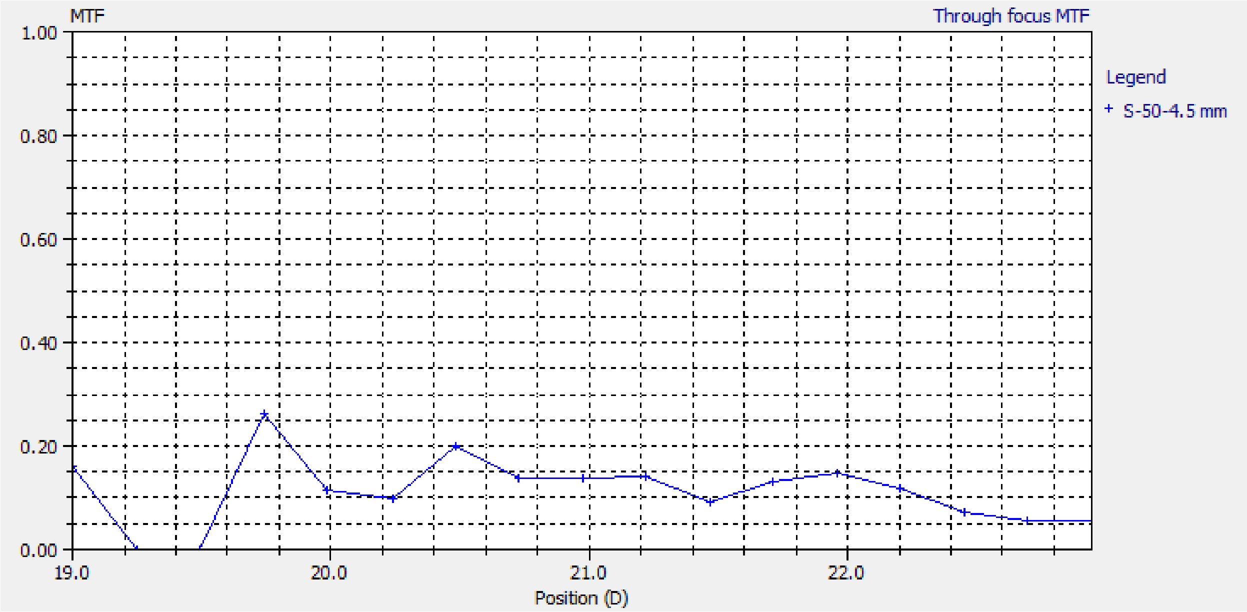


Figure 34: TFAT00 Through Focus MTF - 3 mm Pupil

4.5mm Pupil

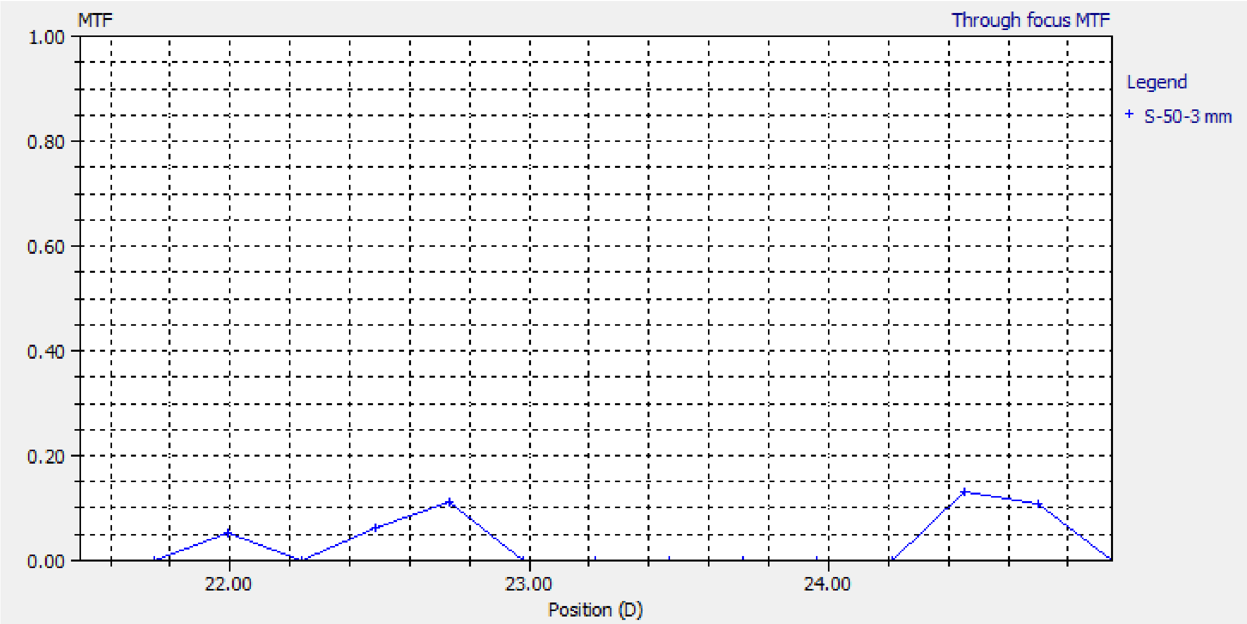


Figure 35: TFAT00 Through Focus MTF - 4.5 mm Pupil

The results from the charts above are logical. The TFAT00 is a Trifocal lens, meaning that it should have three MTF peaks. This lens has a power of 20D and an add power of 2.2 and 3.2. Meaning, there should be peaks around 20D, 22.2D, and 23.2D. This can be seen in the two plots above. The 3 mm has peaks at 22D, 22.75D, and 24.2D. The 4.5 mm pupil seems to have its peak at 19D, 19.8D, 20.5D.

Monofocal IOL

3 mm Pupil

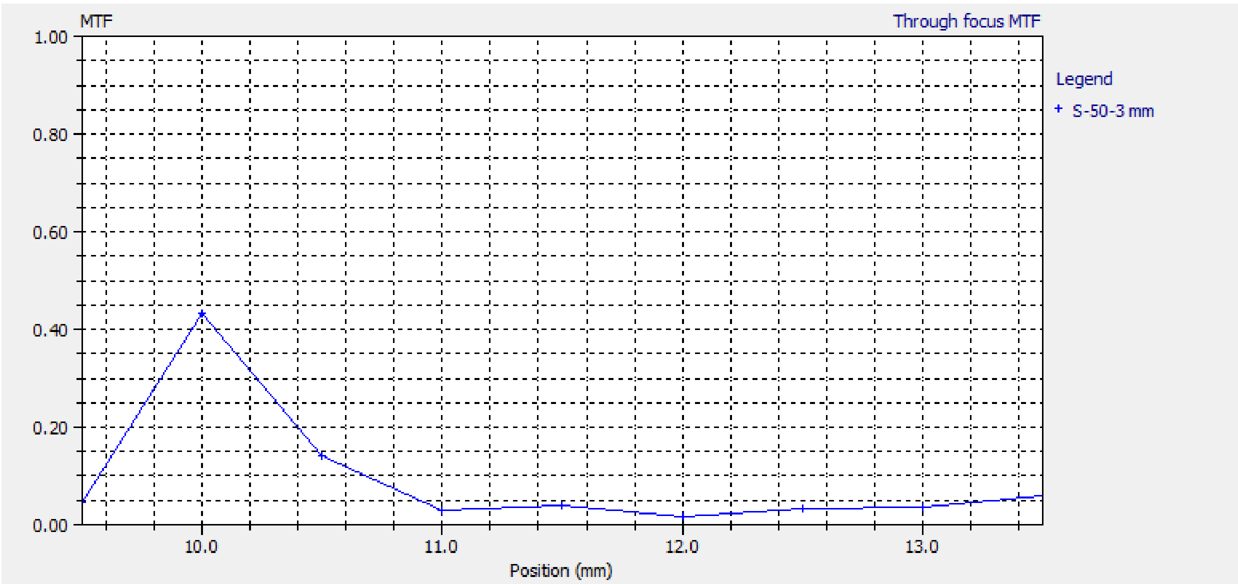


Figure 36: Monofocal Through Focus MTF - 3 mm Pupil

4.5 mm Pupil

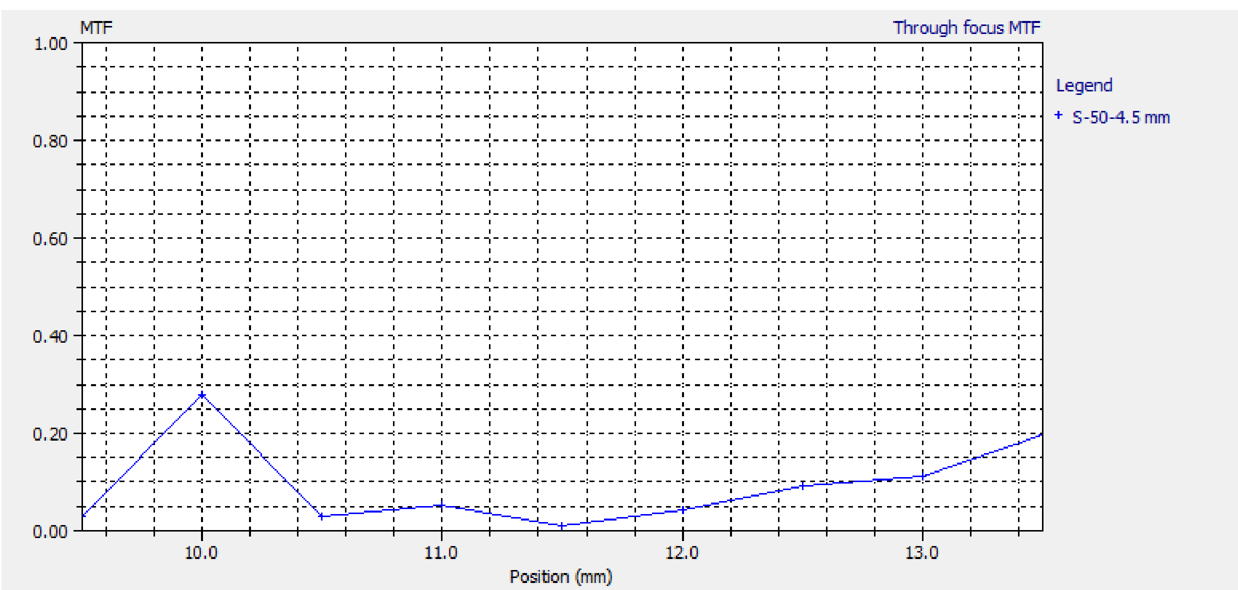


Figure 37: Monofocal Through Focus MTF - 4.5 mm Pupil

The results for the Monofocal lens appear to be accurate. Monofocal lens should only have one MTF peak and this can be seen within the results. At the 10 mm position, there is a MTF value of 0.28 which is significantly higher than the rest.

3.2.3 MTF with Tilt

3.2.3.1 Introduction

In modern cataract surgery, where an IOL is being inserted, IOL tilt has the potential to induce astigmatism and higher-order aberrations. Lens tilt is defined as the angle between IOL optical axis and the baseline axis, shown in Figure 38. The aberration theory states that a beam of light which is entering a spherical lens obliquely will produce a marginal oblique astigmatism. The tilt is usually at a magnitude range between 5 and 6 degrees and is usually greater around the vertical axis.

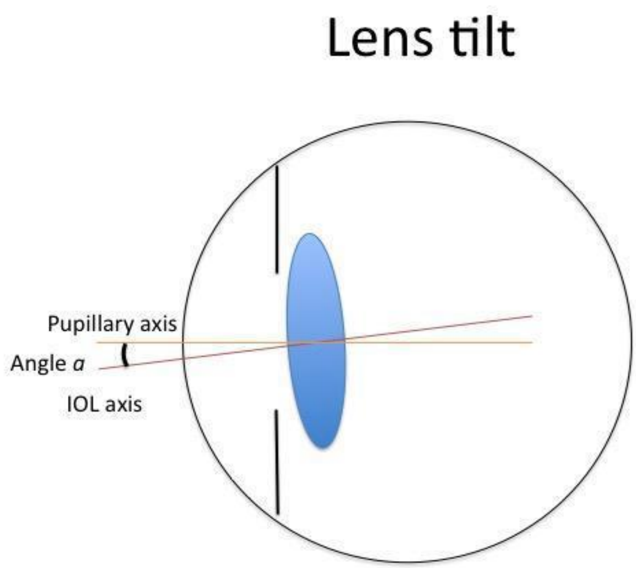


Figure 38: Lens Tilt

3.2.3.2 Set-Up

Setting up the PMTF to test for MTF with tilt first requires the user to complete the PMTF startup explained in part 3. Once the PMTF startup has been completed, the user can start on the following steps.

As mentioned before in section 2.1, to measure MTF, the target pattern must be placed in either horizontal edge or vertical edge. Horizontal edge is for sagittal MTF measurements while the vertical edge is for tangential MTF measurements.

The first step in testing the MTF with tilt, is adding the tilt tool to the eye model. This requires the user to remove the flat surface on top of the eye model. This is done easiest with the eye model not attached to the PMTF. The left side of Figure 39 shows the flat tool on top of the eye model and the right side of the tool shows the tilt tool. To remove the flat tool, or whatever tool is attached, the user must place a hex key within the hole circled in Figure 39. Figure 40 shows the hex key placed within the hole.

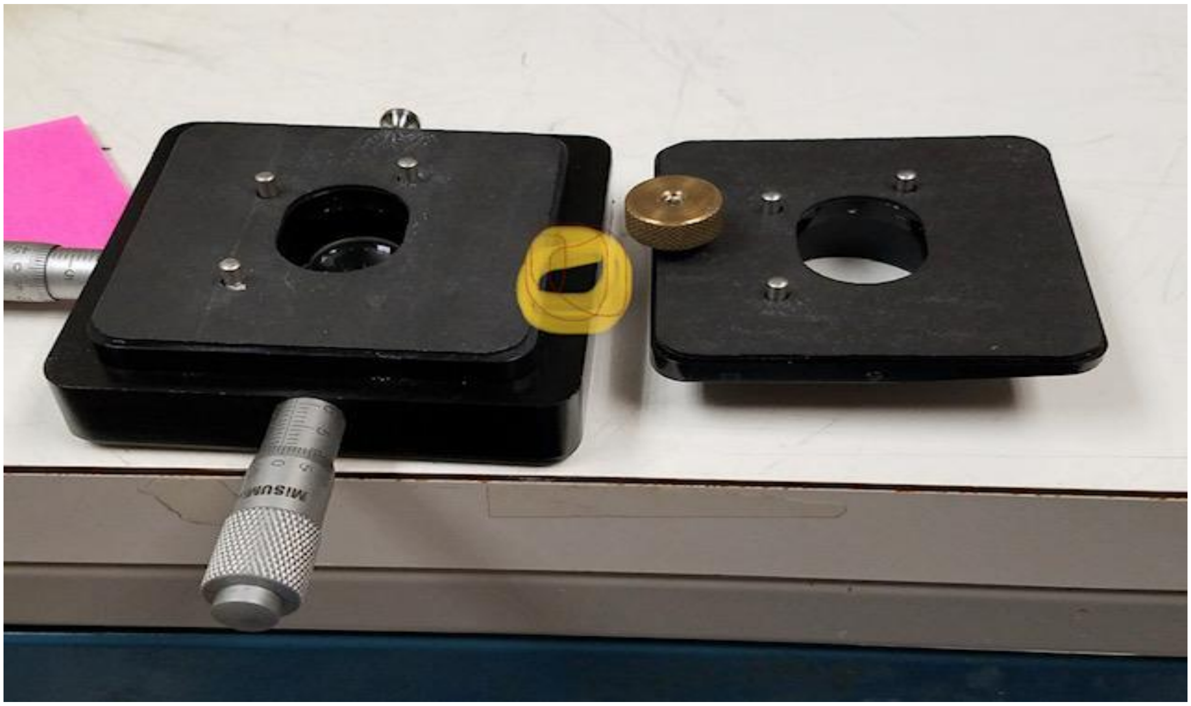


Figure 39: Flat Tool and Tilt Tool

Figure 40: Hex Key within Eye Model

Once the hex key is placed within the eye model, the user should move the X knob till the hex pops into the hole. Once it pops in, the user can unscrew the flat tool and place on the tilt tool. Place the eye model back into the PMTF and place the IOL onto the eye model.

On the software, the user should change the target pattern to the horizontal edge and now the software will record live MTF measurements. The live image should look like Figure 41. To move the IOL in a 5 degree tilt, the user should screw the gold knob till the tool's slanted side is touching the eye model. Figure 42 shows the tool at a 0 degree tilt and Figure 43 shows the till at a 5 degree tilt.

Figure 41: Example of Horizontal

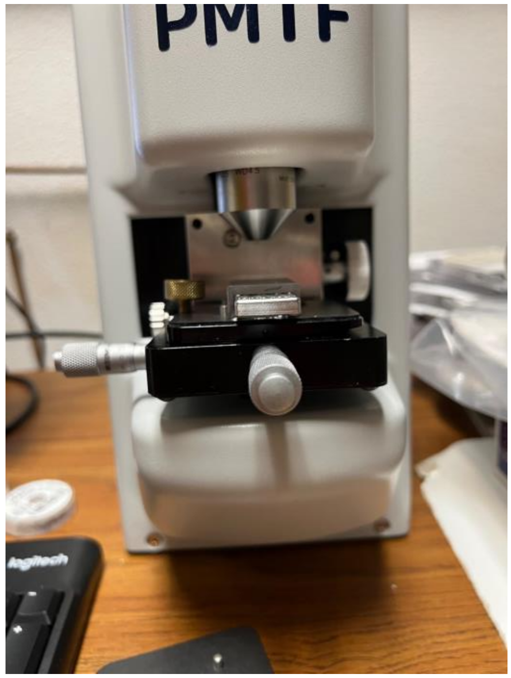


Figure 42: 0 Degree Tilt

Figure 43: 5 Degree Tilt

Note: When moving the IOL to a 5 degree tilt, the live image will look like figure 44. When the live image looks like this, there will be no MTF measurements. To fix this error, move the X table till the live image looks similar to the one in Figure 44.

Figure 44: Live Image at 5 Degree Tilt w/o Correction

3.2.3.3 Results

Alcon TFAT00

0 degree Tilt at 3 mm Pupil

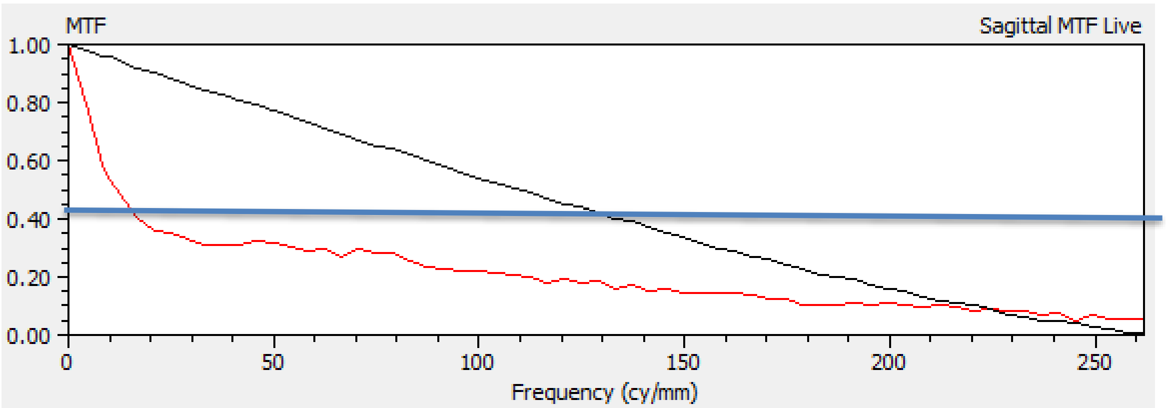


Figure 45: TFAT00 MTF w/0 Degree Tilt at 3 mm Pupil

5 Degree Tilt at 3 mm Pupil

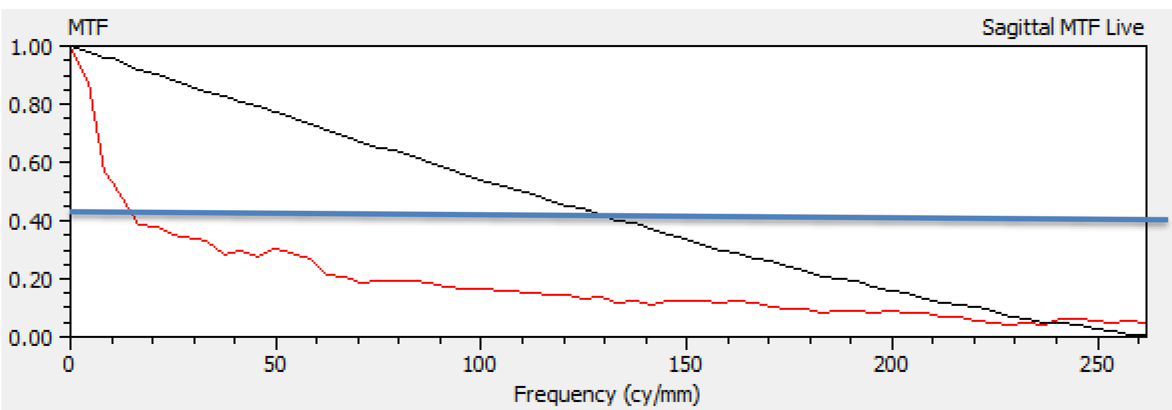


Figure 46: TFAT00 MTF w/5 Degree Tilt at 3 mm Pupil

0 Degree Tilt at 4.5 mm Pupil

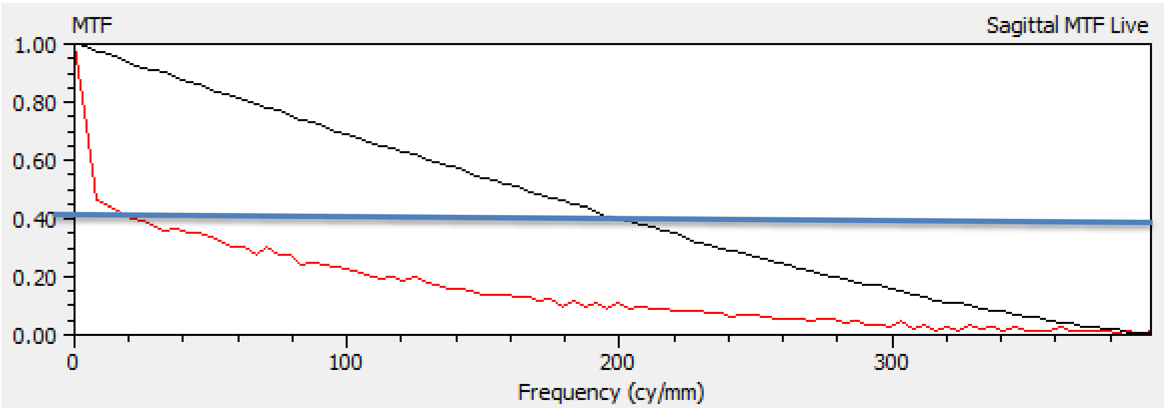


Figure 47: TFAT00 MTF w/0 Degree Tilt at 4.5 mm Pupil

5 Degree Tilt at 4.5 mm Pupil

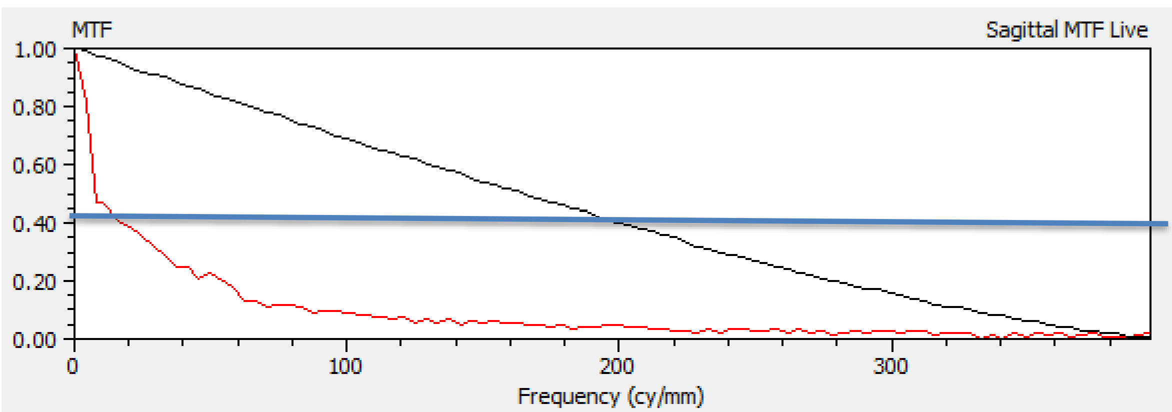


Figure 48: TFAT00 MTF w/5 Degree Tilt at 4.5 mm Pupil

Monofocal

0 Degree Tilt at 3 mm Pupil

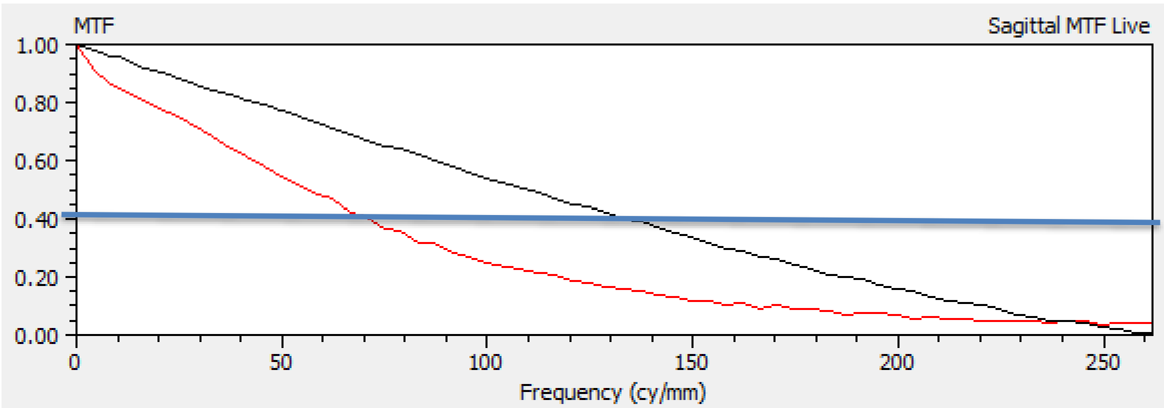


Figure 49: Monofocal MTF w/0 Degree Tilt at 3 mm Pupil

5 degree tilt at 3 mm pupil

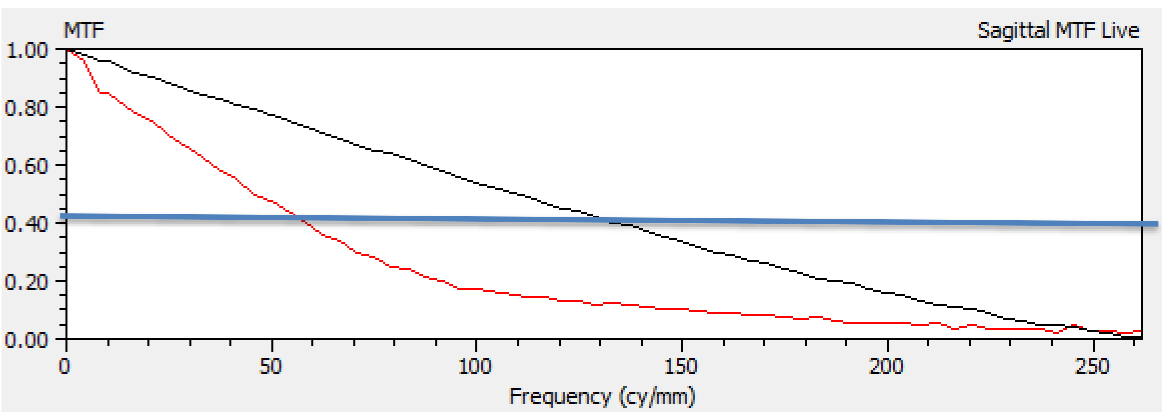


Figure 50: Monofocal MTF w/5 Degree Tilt at 3 mm Pupil

0 degree tilt at 4.5 mm pupil

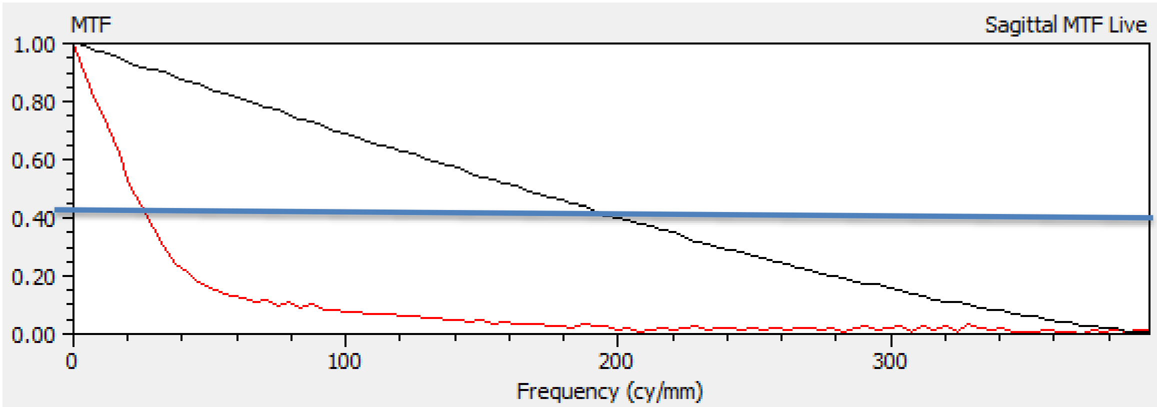


Figure 51: Monofocal MTF w/0 Degree Tilt at 4.5 mm Pupil

5 degree tilt at 4.5 mm pupil

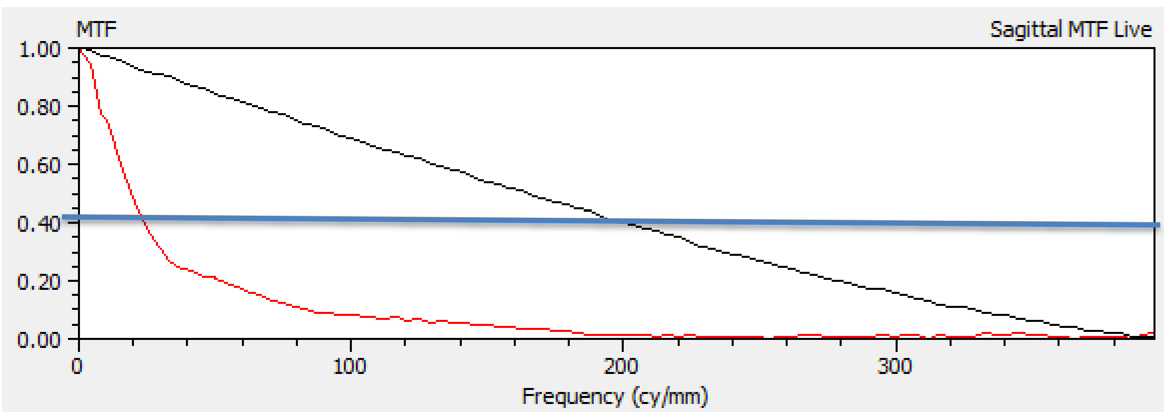


Figure 52: Monofocal MTF w/5 Degree Tilt at 4.5 mm Pupil

The results show that both of these lenses react well to tilt. However, the results show that the Monofocal lens reacts better to the tilt than the Trifocal results. The Trifocal MTF results do not have a significant difference within the 3 mm pupil tilt, but the 4.5 mm pupil results show slight change between the MTF values within the 100 cy/mm. The 5 degree tilt has a slight steeper decrease in MTF with the 100cy/mm.

The Monofocal lens, on the other hand, has very similar MTF values for correlating pupil sizes.

3.2.4 MTF with Decentration

3.2.4.1 Introduction

A dislocated IOL is rare, yet a very serious complication. This happens when the IOL moves out of its normal position in the eye. Dislocation may present as phacodonesis, simple decentration, or complete dislocation of the lens. Decentration refers to the loss of IOL centration.

One thing to note is that even with successful surgeries where the surgeon manually aligns the IOL to the center of the pupil, the placement can never be perfect and the IOL can move during the healing process. This test is to determine how sensitive the IOL is to lateral displacement.

3.2.4.2 Set-Up

Setting up the PMTF to test for MTF with decentration, first requires the user to complete the PMTF startup explained in part 3. Once the PMTF startup has been completed, the user can start on the proceeding steps.

Setting this procedure is very similar to the set-up of MTF with tilt, however, the user will not be using the tilt tool and will use the same flat tool as the other procedures. On the software, the user should change the target pattern to vertical edge and now the software will record live MTF measurements.

When the user is ready to receive decentration measurements, the user will turn the X table knob. The testing procedure conducted within this report is a 1 mm decentration, which comes from ISO’s testing procedures for decentration.

4 Conclusion

In conclusion, this report discusses the uses of the Power and Modulation Transfer Function (PMTF) for assessing optical performances of intraocular lenses (IOLs). The PMTF, developed by Lambda-X, is a valuable tool for evaluating the mechanism of action of different IOL structures. It follows ISO11979-2 standard and measures dioptric power, resolution efficiency, and MTF of IOLs using various targets and setups. The PMTF is applicable for both Monofocal IOLs and Trifocal IOLs. It provides insights for both research and production environments in the field of ophthalmology.

The Through-Focus USAF Target method is a pivotal tool for evaluating imaging system performance, particularly in assessing lens resolution efficiency. The deliberate design of the USAF target, featuring elements of varying spatial frequencies, facilitates simultaneous testing of vertical and horizontal resolutions. Its strategic arrangement, with higher resolution elements at the center and lower resolution elements at the edges, proves advantageous for zoom lens assessments. The obtained results, by Alcon’s TFAT00 IOL USAF target and Monofocal IOL USAF target, are showcased on Table 1. The Trifocal IOL resulted in three MTF peaks observed: the first around 20.8D, the second around 21.5D, and the third around 23D, aligning with expectations for a Trifocal IOL. The Monofocal IOL resulted in one MTF peak observed: the single peak around 22.8, aligning with expectations for a Monofocal IOL. The obtained results for the Through-Focus USAF Target method, aligned with ISO11979-2 standards. It streamlines testing procedures within the PMTF system and provides insightful results, including specific values, crucial for the improvement and certification of imaging systems.

The Through-Focus MTF analysis serves as a crucial method for comprehensively evaluating lens performance, providing valuable insights into the behavior of lenses. The setup process, guided by ISO11979 standards, involves configuring parameters such as scanning positions, step values, and aperture sizes. The presented results for Alcon TFAT00 with 3 mm and 4.5 mm pupils demonstrate the method's effectiveness in capturing expected Trifocal lens behavior, with MTF peaks around 19.9D, 20.5D, and 22D for 3 mm pupils and 22.0D, 22.7D, and 24.4D for 4.5mm pupil. Notably, variations in peak values between different pupil sizes underscore the lens's would not pass the ISO requirements. The MTF value being in the 0.22 range, lower than 0.43 (requirement). Secondly, Alcon states that the lens has a power of 20D and an add power of 2.2 and 2.3. Meaning, there should be peaks around 20D, 22.2D, and 23.2, which can also be seen to be incorrect and inconsistent for different pupil sizes based on the results. The presented results for the Monofocal IOL with 3 mm and 4.5 mm pupil demonstrates results of 10D. The Monofocal IOL align with expectations. Through-Focus MTF analysis thus emerges as a robust and practical tool for gaining a comprehensive understanding of lens performance under varying focus and aperture conditions.

The assessment of MTF with tilt proves to be a critical aspect in modern cataract surgery, where IOL tilt can potentially induce astigmatism and higher-order aberrations. The lens tilt, defined as the angle between the IOL optical axis and the baseline axis, becomes particularly relevant in maintaining optical integrity. The setup for MTF testing with tilt, following the PMTF startup, involves incorporating the tilt tool into the eye model and adjusting the target pattern to horizontal edge for sagittal MTF measurements. The results, exemplified by the Alcon TFAT00 and Monofocal lenses different pupil sizes, reveal that both lenses react well to tilt. Notably, the Monofocal lens demonstrates a more consistent MTF response across varying pupil sizes and tilt angles compared to the Trifocal lens, where slight changes in MTF values are observed, particularly at 4.5 mm pupil size and 5 degrees tilt. The overall description can be seen below on Table 2. These findings underscore the significance of MTF with tilt analysis in evaluating lens performance, with implications for optimizing outcomes in cataract surgery.

In the exploration of MTF with Decentration, the focus is on assessing the sensitivity of an intraocular lens (IOL) to lateral displacement, a critical consideration given the potential complications associated with IOL dislocation. Dislocation, though rare, can manifest as phacodonesis, simple decentration, or complete dislocation of the lens, with decentration referring to the loss of IOL centration. The test aims to evaluate the impact of lateral displacement on IOL performance, recognizing that even with successful surgeries, the IOL's placement may never be perfect, and it can shift during the healing process. The setup process closely resembles that of MTF with tilt, with the user changing the target pattern to a vertical edge on the software to record live MTF measurements. The testing procedure in this report focuses on a 1 mm decentration, following ISO's testing procedures.

PMTF Results (Through-Focus)										
		Through-Focus USAF Target		Through-Focus MTF						
		Expected Peaks	Resulted Peaks	Expected Peak 1	Actual Peak	Expected Peak 2	Actual Peak	Expected Peak 3	Actual Peak	
3mm Pupil	Monofocal	1	1	N/A	10D	N/A	N/A	N/A	N/A	
	Trifocal	3	3	20D	19.9D	22.2D	20.5D	23.2D	22D	
4.5mm Pupil	Monofocal	1	1	N/A	10D	N/A	N/A	N/A	N/A	PASS
	Trifocal	3	3	20D	22D	22.2D	22.7D	23.2D	24.4D	FAIL

Table 1: PMTF Results (Through-Focus)

PMTF Results (Tilt)						
Check Consistency Check if MTF > 0.43		50 cy/mm (20/40)		100 cy/mm (20/20)		
		0° Tilt	5° Tilt	0° Tilt	5° Tilt	
3mm Pupil	Monofocal	0.50	0.50	0.25	0.20	
	Trifocal	0.35	0.35	0.25	0.20	
4.5mm Pupil	Monofocal	0.17	0.20	0.10	0.10	PASS
	Trifocal	0.35	0.25	0.25	0.10	FAIL

Table 2: PMTF Results (Tilt)

5 Other Challenges for IOLs

5.1 Diffractive Characteristic

All information presented in the following section is sourced from Jim Schwiegerling's "Intraocular Lenses" chapter.

One of the optical phenomenon that is exploited to create multifocal optics is diffraction. Multifocality in IOLs are achieved either through diffractive or refractive optical approaches. Diffractive multifocal IOLs intentionally induce diffraction so that the waves exiting the lens will have two or more distinct focuses at different distances. The main distinction between different types of optical approaches that achieve multifocality is that the out of focus light in the diffractive multifocal tends to be more spread out uniformly over a larger area, which is less noticeable.

Multifocal optics with diffractive structures have often been misunderstood because they "tend to move away from the geometrical picture of light rays bending the surface of the lens." Instead of following the geometrical picture. These lenses use the wave nature of light. Multifocal IOLs have concentric annular zones that are created in the face of the lens. The *j*th zone occurs at a radius, shown below,

$$r_j = \sqrt{2j\lambda_o F}$$

where λ_o is the design wavelength and F is the focal length of the add power. The height of the step and the dimensions of the zones control the degree of multifocality of the lens. The height of the step around the boundaries of each zone will determine how much of the light is put into the add portion. The step for most multifocal diffractive lenses is determined so that the peaks of an individual diffractive zone lines up with the, ”troughs of the next larger diffractive zone immediately following the lens.” During the process of waves propagating to the retina, the waves from different diffractive zones will mix and there will be two distinct regions of constructive interference that will correspond to the main two focuses of the multifocal lens. The optical phase profile $\Phi(r)$ of the diffractive is show as

$$\phi(r) = 2\pi\alpha\left(j - \frac{r^2}{2\lambda_o F}\right) \qquad r_j \le r < r_{j+1}$$

where α is a fraction of the 2 pi phase delay and the diffraction efficiency is shown as

$$\eta_m = \mathrm{sinc}^2[\mathrm{m} - \alpha]$$

When m = 1, the energy is distributed into a +1 diffraction order and the power of the IOL for this diffractive order is underlying the refractive power of the IOL plus the power of +1/F provided by the diffractive structure. The amount of energy going into each of the diffractive orders is symbolled as η_0 and η_1, respectively. Energy is then sent to the higher diffractive order with an efficiency of η_m and an add power of m/F to the refractive power of an IOL. Reference 1 shows a summarized app power and the diffraction efficiency for cases where α = 0.5.

Add Power and Diffraction Efficiency for $\alpha = 0.5$ and $F = 250$ mm

Diffraction Order, m	Diffraction Efficiency, η_m	Add Power
−1	4.5%	−4 D
0	40.5%	0 D
+1	40.5%	4 D
+2	4.5%	8 D
+3	1.6%	12 D

Reference 1: Add Power and Diffraction Efficiency [Schweigerling, 2010]

As shown, most of the energy goes into either the 0 or the +1 diffraction orders.

Biasing distances vision through a modified version of the step height or apodization tends to mostly improve the performance over conventional equal-split diffractive lenses with larger pupil diameters. Additionally, stray light effects, flares, and haloes can all be seen with diffractive lenses. Note that apodization of the IOL tends to markedly dampen stray light effect for larger pupils. Overall, diffractive lenses tend to provide superior visual performances when compared to zonal refractive lenses.

5.2 Straylight Analysis

All content in the subsequent section is derived from the research paper “Ring-shaped dysphotopsia associated with posterior chamber phakic implantable collamer lenses with central hole” authored by Youngsub Eom, Daewook Kim, Dongok Ryu, Jun-heon Kim, Seul Ki Yang, Sug-\Whan Kim, and Hyo Myung Kim.

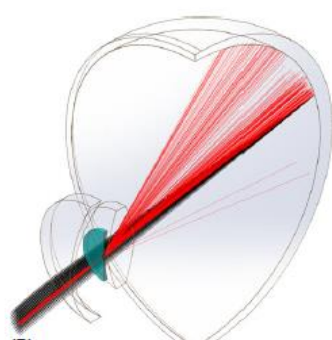
All monochromatic analysis, light wavelength of 546 nm, was preformed for all cases to precent chromatic aberration related effects so that the researchers could confirm that the simulation results only included stray light effects due to the central hole. The pupil irradiance was fixed for all simulation cases and more than thirty million rays were traced for each case so that the researchers could produce statistically reliable results.

Stray light is a term that generally applies to any unwanted light in an optical system. When light travels where it is not intended to in an optical layout, it can cause a variety of issues including multiple images, reduced contrast in imagery, and many more issues. However, stray light is not the detrimental in an optical system. There are a few approaches to mitigate the effects of stray light.

The researchers goal to determine the stray light pattern was to “investigate the fundamental mechanism of hole-induced ring-shaped dysphotopsia, a series of retinal images were simulated using point sources at infinity with well-defined field angles (0, -1, -5, -10 and -20°). Each of these field angles would produce a corresponding retinal image patter that would represent the stray light pattern caused by the inner wall of the central hole.

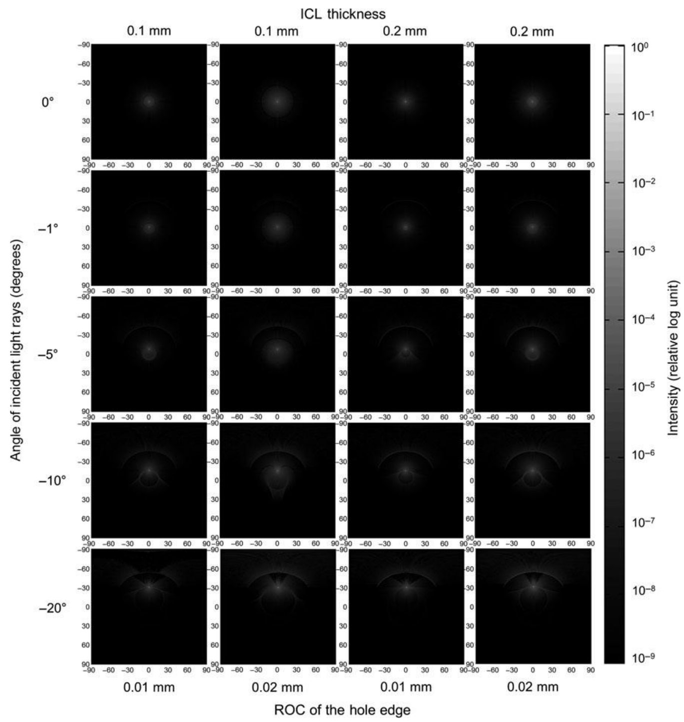
To verify the non-sequential ray tracing, the researchers used the ratio of the radiant power of the stray lights to the total light from the ICl-implanted eye hole to calculate the angle of incidence of the light rays from 0 degrees to 50 degrees at 5 degree intervals.

The source of their ring-shaped stray light pattern was shown on two non-sequential ray-tracing plots that compared the conventional ICL with the hole ICL case. The conventional ICL would focus all of its rays on one single point and the hole ICL would produce arc patterns which can be seen on retina [Reference 2]. The stray light, shown in red in the image [Reference 2], was created by the refraction from the inner wall of the hole, anterior, and posterior ICL surfaces.



Reference 2: Arc Pattern Shown on Retina [Eom et al. 2016]

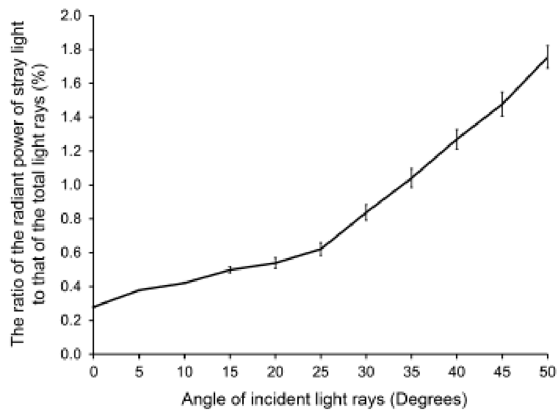
The image below [Reference 3] shows the "final retinal images measured in log-scale irradiance for multiple field angles (0, -1, -5, -10 and -20°) through hole ICL implanted eyes." The stray light can clearly be observed within the human eye dynamic range. The two main patterns observed are the patterns from the glare and the patterns from the arc images. It can be seen that the pattern would generally increase as the field angle would increase.



Reference 3: Final Retinal Images Measured in Log-Scale Irradiance
[Eom et al. 2016]

The researchers determined that the location of the ring-shaped dysphotopsia associated with the hole ICL corresponded to the arc pattern for the -5 degree field angle. This means that the convolution of stray light patterns created by the Lambertian source, from 0 degree to +/- 2.9 degrees, "ray angles with respect to the optical axis contributed to the ring-shaped dysphotopsia pattern on the retina.

The radiometric analysis states that the ratio of radiant power from the stray light to the overall total light rays increases as the angle of the incidence of the light rays also increase. The calculated SDs from the researchers were determined to be in the ranges of 0.004 to 0.071 percent, show in the image below [Reference 4].



Reference 4: Calculated SDs [Eom et al. 2016]

The researchers' results were able to successfully demonstrate that the hole ICL evokes glares and ring-shaped dysphotopsia during experimental conditions using an extended Lambertian source. This is a significant correlation to the light sources in daily life. Their component level experiment was used to investigate individual stray light patterns with the light source's spatial and angular distribution. The stray light patterns was determined to be a complex function and required a case by case simulation. However, the convolution of the stray lights were patterns that were formed like ring-like shapes.

References

[1]Carson, Daniel, et al. “Optical Bench Performance of 3 Trifocal Intraocular Lenses.” *Alcon Research*, Sept. 2016.

[2] Eom, Youngsub, et al. *Ring-Shaped Dysphotopsia Associated with Posterior Chamber Phakic Implantable Collamer Lenses with a Central Hole*. 2016.

[3] Jung, Hoon, et al. “Intraocular Lens (IOL) Tilt and Astigmatism.” *Shruti Aggarwal*, 23 Sept. 2021.

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