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Adjustable adaptive compact fluidic phoropter with no mechanical translation of lenses

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Abstract

We demonstrate a compact optical phoropter consisting of adjustable astigmatic and defocus lenses. The lenses are fluidically controlled and allow for an arbitrary refractive error to be corrected without mechanically moving lenses. Shack–Hartmann measurements were used to characterize the optical properties of the individual lenses. The lenses were then assembled into the phoropter and controlled with three separate fluid controls. The phoropter was verified by correcting the vision of a model eye with an induced refraction error.

Ophthalmologists and optometrists commonly use a phoropter to determine refractive error in patients. The process typically involves subjective feedback from the patient using a repetitive verbal cue when ophthalmic trial lenses are mechanically switched in and out to change the refraction. The process relies on subjective feedback from the patient but is effective in determining a suitable prescription. However, this process is time consuming for both the patient and the examiner. Incorporation of fluidic lenses into the phoropter will allow a continuously varying optical wavefront that results in reduction of the time required for the examination, since the process could be computer controlled. The physical size and complexity of the standard phoropter is problematic from a manufacturing and deployment perspective, and the development of a fluidic lens system offers the potential to simplify and greatly reduce the size of the instrument. The phoropter monacle that was developed in this study measures 13.7 mm thick and 44.5 mm in diameter (Fig. 1). A pair of these phoropter monacles could be head mounted to allow the patient to move his or her head during an examination, allowing the patient to receive a better sense of the amount of visual improvement under natural conditions. Fluidic lenses that are based on a flexible membrane use fluidic pressure to control the curvature of the flexible membrane. This control allows alteration of the optical wavefront in a continuous and consistent manner. Fluidic lenses have been used to circumvent the need to mechanically move a lens to provide optical zoom [1–3]. Similarly, we have capitalized on recent demonstrations of fluidic lenses capable of defocus (–20D to 20D) and astigmatic (0 to 8D) correction [4,5] to construct a phoropter without the need to mechanically introduce lenses into the view of the patient. The fluidic lenses have low values of higher-order Zernike terms, as demonstrated by their high visual quality with a visual Strehl ratio computed in the frequency domain of greater than 0.75 for the defocus lens and greater than 0.98 for the astigmatic lens [5]. A phoropter was constructed using two astigmatic lenses oriented at 45° to each other and combined with a defocus lens, which allows for continuous spherical and cylindrical correction.

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To the best of our knowledge, this is the first demonstration of a phoropter based on fluidic lenses.

The phoropter is composed of one defocus lens and two astigmatic fluidic lenses that work in unison to provide arbitrary sphero-cylinder refraction. Figure 2 illustrates the two lens types. Each of the lenses is composed of an elastic membrane that is secured with a metallic retaining ring and contains a 12.5 mm glass rear surface, which is the clear aperture of the lens. A separate fluid reservoir is present for each lens that is 1.65 mm thick and allows independent control of the lenses. Adding or removing fluid from the chamber allows the defocus lens to provide both positive and negative optical power. The defocus lens has a circular restraining aperture of 23 mm in diameter, which is used to secure the elastic membrane. The astigmatic lenses have a rectangular retaining ring that results in a restraining aperture of 30.0 mm×16.0 mm, which is used to secure the elastic membrane. The axes of the two astigmatic fluidic lenses are oriented at 45° to each other.

The elastic membrane was fabricated using Sylgard 184 polydimethylsiloxane (PDMS), which is commercially available from Dow Corning. The PDMS was fabricated by mixing the Sylgard and its curing agent in a 10:1 ratio. The mixture was then poured into a mold that contained a glass plate to provide an optically smooth surface for one side of the membrane. Flatness for the other surface of the membrane is not as critical, since it is in contact with a fluid that reduces the variation in index of refraction. The PDMS membrane was then out-gassed in a vacuum to remove air bubbles. Finally, the membrane was baked in an oven at 90°C for 1 h to completely cure the PDMS.

The structural portion of the lenses was machined from aluminum and anodized black. Deionized water was used for the fluid in the lenses described in this manuscript. Two fluid ports are present for each lens; one port is used to control the fluidic volume of the lens, while the other port is used to remove air during filling of the lens. A syringe pump is used to control the fluidic volume of the lens. By varying the fluid volume the elastic membrane can be varied from concave to convex, allowing both positive and negative power corrections to be achieved in both lens types.

The individual fluidic lenses were measured using a Shack–Hartmann wavefront sensor to generate refractive measurements as a function of fluidic volume. The measurement used a green He–Ne laser ($\lambda = 543$ nm), which is near the maximum photopic luminous efficiency of the human eye. Light from the laser is expanded to form a collimated beam, which is approximately 1 cm in diameter. The wavefront sensor is based on a 64×64 element lenslet array consisting of lenses with a focal length of 19 mm and arranged on 250 μ m centers. The resultant focal spot image was measured with a 1/3 in. CCD camera (Point Grey Research FL2-14S3M) that has 7.6 μ m pixels. The spot pattern is analyzed to determine the shape of the wavefront emerging from the fluidic lens combination as a function of fluid volume. Initially, the desired cylinder and axis value for the phoropter are found on the astigmatic lens plot [Fig. 3(a)] using the solid lines. The fluidic volumes for each of the astigmatic lenses can then easily be determined from the abscissa and ordinate of the graph. Next, the dashed lines [Fig. 3(a)] can be used to determine the amount of defocus generated by the astigmatic lenses, which is combined with the desired spherical power for the phoropter. Finally, using Fig. 3(b) the correct fluid volume for the defocus lens is determined.

Video of the Shack–Hartmann spot diagram was taken to determine rates of change for the optical power of the phoropter. A change of −31.95 diopters/s of spherical power and 30.9 diopters/s of astigmatic power was seen to give a spherical equivalent power of 16.5 diopters/s. This rate of change is sufficient for typical ophthalmic applications.

Imaging experiments were performed through the phoropter using a model eye (Fig. 4). The model eye was composed of a 20D intraocular lens that was inserted into a saline-filled chamber. A 6 mm pupil was used after the chamber to approximate the pupil of the eye, and this became the system pupil. Next, the cornea was approximated using a 40D lens. Refractive error in the eye was obtained by inserting spherical and cylindrical trial lenses in front of the model eye. The fluidic phoropter was placed in front of the model eye and adjusted to compensate for the refractive error induced in the model eye.

Initially, an image of a cat was taken through the model eye when the phoropter was set for zero optical power [Fig. 5(a)]. Next, ophthalmic trial lenses were added to the model eye to give a refractive error of 2D spherical and 1D cylinder at 120°. An image was then captured through the uncompensated phoropter as shown [Fig. 5(b)]. Finally, the fluidic phoropter was adjusted to compensate for the induced sphero-cylinder error, and the resultant image is shown [Fig. 5(c)].

In summary, we have presented a fluidic phoropter that is composed of three fluidic lenses. The three lenses work together to provide an ophthalmic refraction composed of sphere, cylinder, and axis. A model eye was used to confirm the optical quality and the ability to provide a refractive correction. The physical size of the phoropter is small and compact, allowing the device to be easily used for ophthalmic applications.

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Fig. 1.

Figure of (a) a conventional phoropter and (b) a monacle of the fluidic phoropter. The difference in physical size of the two instruments is readily apparent.

Defocus Lens

Astigmatic Lens

Astigmatic Lens

Fig. 2.

Diagram of an exploded view of the phoropter construction. The two astigmatic lenses are positioned at the bottom of the diagram, and the defocus lens is at the top.

(a)

(b)

Fig. 3.

(a) Contour plot of the astigmatism and angle generated by the two astigmatic lenses for a given fluid volume is shown. Also present in the dashed lines is the amount of defocus produced by the astigmatic lenses. (b) Also shown is the amount of defocus optical power generated by the circular lens as a function of the fluidic volume.

Fluidic Phoropter

Model Eye

Fig. 4.

Schematic diagram of the model eye and phoropter is shown in the figure. Ophthalmic correction lenses are used to induce spherical and cylindrical refractive error in the model eye. The details of the system are discussed in the text.

Fig. 5.

Image results are taken with the model eye and the phoropter. The cat is pictured (a) with no power to the phoropter, (b) no power to the phoropter and an induced refraction error of 1D cylinder and 2D sphere at 120°, and (c) the refractive error is corrected by the phoropter. Other refractions demonstrated similar image quality.