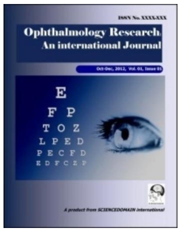

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Multimodal Views of the Human Retina

A. Terry Bahill[1*] and Patrick J. Barry[2]

[1]Systems Engineering, University of Arizona,1622 W. Montenegro, Tucson AZ USA, 85704-1822, USA.
[2]Envision Eye Care Center, Tucson Arizona, USA.

Authors' contributions

Author ATB designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author PJB provided the medical instruments, measurements, clinical images and medical expertise.

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ABSTRACT

Aims: To show the relationships among subject-reported measures of vision, the view through an ophthalmoscope, the view through a slit lamp, the view through a clinician's eye, optical coherence tomography (OCT) images, fundus photos, visual field diagrams and Optomap images.

Methodology: Over 1000 clinical ocular measures (taken on one subject over a six-year period of time) were collected, analyzed and summarized. These measures were reduced to 50 images and tables: they were then categorized and filtered, and the essence resulted in the figures contained in this paper.

Results: This paper shows that the retina literature is full of contradictory nomenclature. For example, clinicians use the term *fovea* to name the 1° diameter disk at the very center of the retina and they use the term *macula* to name the 5° diameter ring that surrounds it. Whereas, anatomists use the term *fovea* to name the 5° diameter disk at the center of the retina and they use the term *macula* to name the 20° diameter ring that surrounds it. This paper demonstrates how the same information appears in the subject's reports of vision, a facial photograph, an optical coherence tomography image, a fundus photo and a visual field diagram. Finally, it shows how to map information between these views.

Conclusions: The retina-viewing techniques analyzed in this paper can be compared qualitatively, but differences in the techniques preclude precise superposition of the images. A perfect mapping is impossible: because (among other reasons) the algorithms for transforming three-dimensional (3D) shapes into two-dimensional (2D) images are

**Corresponding author: E-mail: terry@sie.arizona.edu;*

nonlinear and are different for different techniques.

Keywords: Retina imaging; OCT; fundus photograph.

ABBREVIATIONS

HD : High Definition
ILM : Inner Limiting Membrane
OCT : Optical Coherence Tomography
OS : Left eye
OD : Right eye
RPE : Retinal Pigment Epithelium

1. INTRODUCTION

Some ophthalmological diagrams are printed from the subject's point of view and some are printed from the clinician's point of view. For example, the subject would see his left elbow in the lower-left portion of his visual field of view whereas a clinician would see the subject's left elbow in the lower-right corner of a photograph of the subject. Some medical professionals (and their literature) use the term *macula* to name the 5° diameter disk in the center of the retinal, whereas others use the term *fovea* for the same region. Furthermore, there are scores of instruments for viewing the retina. There is no wonder that patients get confused. We think that ophthalmologists and optometrists can use this paper to help explain to their patients the confusing nomenclature and the overwhelming amount of information generated by their plethora of instruments.

Our subject, A. Terry Bahill (ATB), has had a 12 eye surgeries over the last six years. He has been examined and treated by an optometrist, ten ophthalmologists, et al. Over 1000 clinical ocular measurements have been performed on his eyes using various retina-visualizing techniques [1]. These measures were analyzed, summarized and reduced to 50 images and tables: these data were categorized and filtered: then the essence was put into the figures of this paper. Our objective is to show (in layman's terms) the relationships between the following views: through the subject's eye, through an ophthalmoscope, through a slit lamp, through the clinician's eye looking at a face, fundus photos, optical coherence tomography images, visual field diagrams and Optomap images.

1.1 Retinal Distances

One millimeter on the human adult retina corresponds to 3.5º of visual angle (0.286 mm/deg) (with a range of 3.4º to 3.6º). The optic disk (the image of the optic nerve and blood vessels entering and leaving the retina) can be modeled as a disk with a diameter of 6.3º (1.8 mm±0.3). A more complex model is that of an ellipse 6.1º (1.75 mm) wide and 6.5º (1.85 mm) high. On the retina, the center of the optic disk is 15.5º±1.1º (4.4 mm) nasal and 1.5º±0.9º (0.4 mm) superior to the center of the fovea [2,3]. As long ago as 1867 Hulke [4] wrote, "I found the distance of the fovea from the centre of the optic nerve exactly equalled [sic] $1\frac{5}{6}'''$." The triple prime symbol stands for ligne, which equals 2.26 mm. So his measured distance was $1.83''' \times 2.26\frac{\text{mm}}{'''} \times 3.5\frac{\text{deg}}{\text{mm}} = 14.5$ degrees. This is within one standard deviation of the distance given previously.

1.2 Names for Retinal Areas

Different classes of people (e.g. clinicians [like optometrists and ophthalmologists], anatomists, engineers, etc.) have named the areas of the retina differently [5]. This has created confusion. Therefore, we created Table 1 and Fig. 1. to unravel this muddle.

Table 1. Names for areas of the retina, from the center outward to the edge

Description	Approximate disk diameter	Clinical or Classic name(s)	Anatomical name(s)	Characteristics
Center of foveal pit	0 mm, 0º	Center of fovea	Umbo	
Floor of foveal pit	0.29 mm, 1º	Fovea, fovea centralis [4]	Foveola	It has red and green cones, but no blue cones, no rods and no vasculature
Capillary free zone	0.6 mm, 2º	Foveal avascular zone	Foveal avascular zone	It has no arterioles or venules. It is not circular.
Sloping sides of the foveal pit	1.4 mm, 5º	Macula, macula lutea, yellow spot [4]	Fovea, fovea centralis	It is the darkly pigmented *disk* in the center of the retina. It is about the size of the optic disk. It has no rods, only cones.
Foveal pit rim-to-rim	1.85 mm, 6.5°	Foveal pit	Foveal pit	The foveal pit rim is the thickest part of the retina.
Ring around the anatomic fovea	2.9 mm, 10º		Parafovea	Its ganglion cell layer is composed of four to seven rows of cells.
Ring around parafovea	5.7 mm, 20º		Perifovea	Its ganglion cell layer contains two or three rows of cells.
Disk containing all of the above	5.7 mm, 20º	Posterior pole	Macula, area centralis	
Equator	24 mm, conversion to degrees is meaningless			It is the boundary between the anterior and posterior halves of the eyeball.
The edge of the retina.	30 mm from the center of the fovea.	Ora serrata	Ora serrata	It is on the anterior half of the eyeball. There are no rods or cones anterior to the ora

For comparison, the optic disk is about 6.3 degrees in diameter and the sun and the moon are ½ degree in diameter. For a typical man with his arm extended in front of him, the clinical fovea (foveola) (one degree in diameter) is the width of the fingernail on the little finger: the foveal avascular zone (two degrees in diameter) is the width of the index finger at the proximal interphalangeal knuckle: the clinical macula (anatomical fovea) (five degrees in diameter) is the distance between this joint and the tip of the index finger: the parafovea (ten degrees in diameter) is the width of the fist: and the anatomic macula (twenty degrees in diameter) is the width of two fists.[10]

Column 3 of Table 1 is the classic (or clinical or traditional) retina nomenclature, which goes back at least one hundred and fifty years [4]. Column 4 is the anatomic (or histologic) nomenclature. Dictionaries and encyclopedias usually give the clinical nomenclature. Research papers usually use the anatomic nomenclature. For the last two centuries, the clinical macula (the darkly pigmented 5º disk in the center of the retina) has been called the yellow spot or the macula lutea [4]. With red-free light or certain preparations, it may appear yellow: however, in fundus photos, it usually looks dark red. Confusingly, a large number of papers describe the macula lutea as a five-degree oval-shaped *yellow spot* in the center of the retina and then they proceed to show a fundus photo with a five-degree dark *reddisk* marked as the macula.

The foveal pit is the depression in the center of the retina. It was not a regular descriptive feature until cross-sectional views of the retina became common. Now it is a clearly defined landmark. It is easy to measure; the rim-to-rim distance of the foveal pit, 1.85 ±.0.23 mm [6]. However, this large standard deviation shows that the inter subject variability of these retinal metrics is large.

Fig. 1 shows a fundus photo of the retina of the left eye. It has an arc of scar tissue (created by a laser in order to reattach a detached retina) in the upper right corner of the photo and a small area of scar tissue in the lower left corner. The optic disk is circled. The circles in the center show the regions of the retina that are named. The rectangular inset at the bottom is a horizontal cross section of the retina, a slice right through the center of the fovea. On the left side of this rectangle, the surface of the retina starts to dip down into the optic disk.

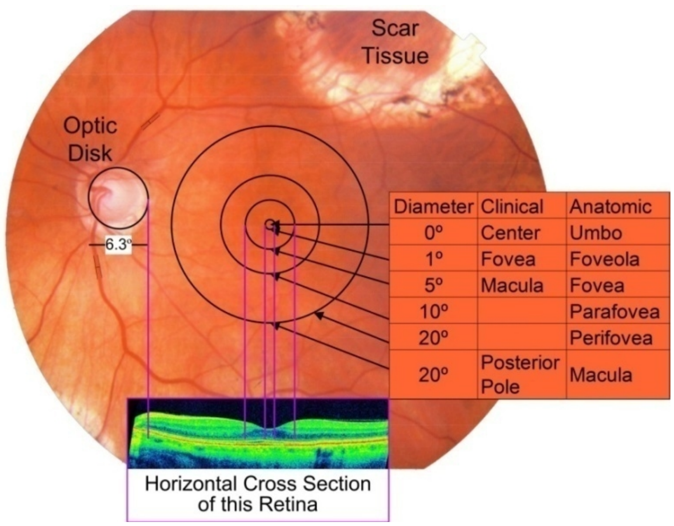


Fig. 1. Names for areas of the retina

2. METHODS

2.1 Visualizing the Retina

In this paper, we will consider the following techniques for visualizing the human retina: subject-reported vision, an ophthalmoscope, a slit lamp, fundus photos, Optical Coherence Tomography (OCT), visual field diagrams and the Optomap instrument. First, in Fig. 2, we show the subject's reported vision of a black-line target composed of concentric squares. The right eye's image (thin green lines) is the same as the visual target. The left eye's image (thick red lines) shows the distortion due to a wrinkled retina (macular pucker). The scotoma in the lower-left quadrant of the figure probably resulted from peeling the inner limiting membrane (ILM).

2.1.1 Documenting the Wrinkled Retina

Creating figure 2 was complex and time consuming. For this subject, the luminance threshold for the left eye is about 1.5 log units higher than for the right eye. Therefore, for these measurements, a 1.5 log unit neutral density filter was fit onto the spectacle lens for the right eye. The subject would fixate on the center of the target and perceive a small portion of the target with peripheral vision. Then he would sketch that small portion of figure 2. He would do this with alternate eyes. This process was repeated about one hundred times. Then a month or so later, the process was repeated again. Details in figure 2 changed slightly and slowly over the years.

The second variant of this process allowed *simultaneous* viewing with the two eyes. Our subject has strabismus because of the first detached retina operation. So at rest, the image seen by his left eye drifts to the right. In this measurement, the target was displayed 2.9 m away from the eyes, so that 5 cm on the target equals one degree on the retina. The neutral density filter was still on the right lens. Then the subject allowed his eyes to cross so that his right eye saw the target in its normal position and simultaneously his left eye saw the target that had drifted to the right. He then the adjusted the sketch of Fig. 2. The two processes produced the same sketch for Fig. 2. This figure is the result of many of measurements taken over several years. But it was worth the effort, because none of our other retina visualization techniques gave resolution this fine.

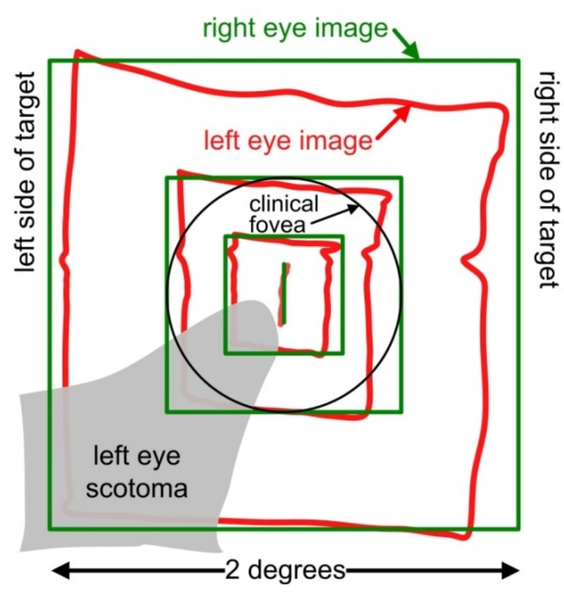


Fig. 2. The subject's viewpoint of a black-line target composed of concentric squares, from [1], reprinted with permission of the authors

2.1.2 Techniques for visualizing the retina

Next, in Fig. 3, we compare several other techniques for evaluating the anatomy and physiology of the retina. The clinician's view of the subject's face is shown in the top row of figure 3. The image of the subject's right eye (OD) is on the left side of the figure and the image of the subject's left eye (OS) is on the right side of the figure. With the exception of this top row in Fig. 3., all of the data in this paper are for one subject, ATB. Fig. 3 shows, from top to bottom, the clinician's view of the subject's face, OCT images of the right and left retinas, horizontal cross sections of the retinas, fundus photos of the retinas and visual fields for the left and right eyes. For each row, the nasal sides of the eyes are in the middle and the temporal sides of the eyes are on the outside. Each column of Fig. 3. has the foveae roughly aligned. The big blue arrows show corresponding locations in the different diagrams. For the right eye, the blue alignment arrow connects the temporal edges of the optic disk in the OCT image and in the fundus photo: this is meant to draw attention to the edge of the fovea in the cross section of the retina. For the left eye, this arrow connects, more naturally, the centers of the optic disks. The blue arrows show corresponding locations. Significant points were lined up as well as possible. However, a perfect mapping is impossible: because (among other reasons) the algorithms for transforming three-dimensional (3D) space into two-dimensional (2D) images are nonlinear and are different for different techniques[1]. Furthermore, the magnification scales are different for each diagram in this figure.

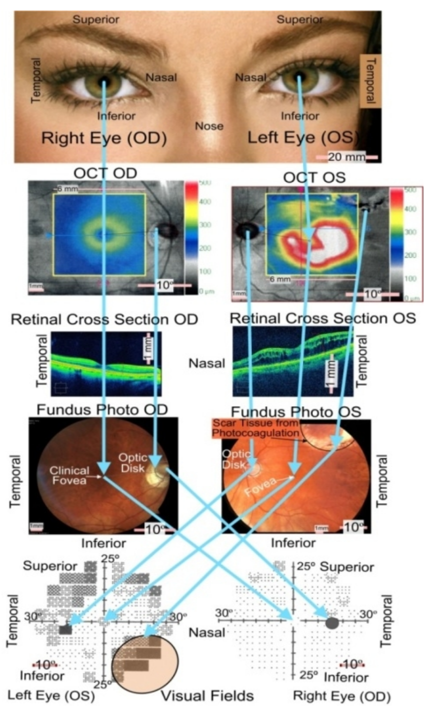


Fig. 3. Shown from top to bottom are the clinician's view of the subject's face, OCT images of the right and left retinas, cross sections of the retinas, fundus photos of the retinas and visual fields for the left and right eyes. Each row has a different scale

[1] There are hundreds of algorithms for transforming three-dimensional information (as on the earth or a globe) onto a two dimensional plane (such as a map or an image). One of the oldest and most familiar is the Mercator projection. Google Earth uses a Simple Cylindrical projection. Each of our ophthalmic instruments uses some algorithmic projection, but we do not know which algorithm is used by which medical instrument.

2.2 Fundus Photos

The fourth row of Fig. 3 shows fundus photos of our subject's right and left retinas. A fundus camera is designed to photograph the interior surface of the eye, including the retina, optic disc, blood vessels, macula and fundus. Using optical lenses, it produces an upright image of the retina for the clinician to see. These images are displayed from the viewpoint of the clinician looking into the subject's face. Therefore, objects that are anatomically in the top part of the retina will appear in the top of the fundus photo. Objects in the nasal part of the retina will appear in the nasal part of the fundus photo. In rows two and four of Fig. 3, the ugly ring in the superior-temporal region of the left eye's fundus photo and OCT image is scar tissue caused by laser photocoagulation. Because this subject was myopic, the optic disk has a white myopic crescent around it, which is more prominent in this subject's right eye. On fundus photos, arteries are lighter, smaller and less tortuous than veins. The subject does not wear spectacles during fundus photography.

2.3 Visual Field Diagrams

Visual field diagrams show what the subject sees when looking forward out of one eye or the other (monocular viewing). Visual field diagrams are printed from the viewpoint of the subject looking out. This causes a 180º horizontal rotation from the fundus photos. The visual field diagrams of the two eyes are usually plotted side by side, with the left eye on the left of the diagram and the right eye on the right of the diagram, as in the fifth row of figure 3. This puts the temporal parts of the visual fields on the sides of the diagram (near the temples) and the nasal parts in the middle. Things that are in the top part of the visual field will appear in the top of the visual field diagram. Anatomically, the center of the optic nerve (the blind spot) is on average 15.5º nasal and 1.5º superior to the center of the fovea. So visually, the blind spot will be about 15.5º temporal of the center of the fovea as indicated with the solid black circles. The dark squares are areas where the subject does not see. The large dark area in the inferior-nasal region of the left eye's visual field corresponds to the scar tissue in the superior-temporal region of the left eye's fundus photo. In contrast to the other retina-viewing techniques, a visual field plot is linear, because the targets are projected onto a horopter screen (roughly speaking, a section of a sphere.) The subject does not wear his or her glasses when viewing targets in a visual fields instrument; however, an appropriate trial lens should be put in the lens holder in front of the subject's eye.

Visual field diagrams are useful for explaining a subject's vision to the subject. For example, this subject must be on the lookout for things that are above and to his left, like a tree limb above his left shoulder, because now he cannot see the limb with his left eye (because of the scotoma) and he cannot see it with the right eye, because the limb would be out of the field of view of the right eye. He used to be able see objects in this area, but now he cannot. He will not be aware of this deficiency unless it is pointed out to him.

2.4 OCT Images

An Optical Coherence Tomography (OCT) instrument images the retina by measuring the echo time delay and magnitude of reflected light. It directs a beam of light through a beam splitter. described for fundus photos. An OCT instrument images the retina by measuring the echo time delay and magnitude of reflected light. It directs a beam of light through a beam splitter. One beam is focused on the subject's retina, and the other is directed at a reference mirror. Light from the incident beam is reflected off retinal structures at different axial depths and merged with light reflected from the reference mirror. All of this information is put into a three dimensional model in the computer. This model can then be enlarged, rotated, sectioned, etc. The subject does not wear spectacles during OCT measurements: instead the operator focuses the retinal image.

The OCT diagrams in the second row of Fig. 3 show the optic disks (black ovals) and blood vessels radiating from them on the nasal edges. The superimposed central square shows (with a color code) the thickness of the retina (specifically the distance between the inner limiting membrane (ILM) and the retinal pigment epithelium (RPE)). The intersections of the red and blue hairlines in the second row indicate the centers of the foveae, as determined by the computer: for the left eye, this point is wrong, probably because the instrument defines the fovea as the area where the retina is the thinnest and this eye's retinal thickness is altered by edema. Next, row 3 of Fig. 3 shows a horizontal cross section of the retina passing through the fovea. For the OS there is fluid (macular edema) under the retina: this appears as black columns above the yellow RPE line.

We have used three different OCT systems: Heidelberg Engineering, the Optos Optomap and Zeiss Cirrus. The following describes the calibration measures for the Zeiss Cirrus OCT. In a Macular Cube 512 x 128 diagram (second row of Fig. 3), the ILM-RPE box overlaid on the fundus photo is 6 by 6 mm. The ILM-RPE thickness box (not shown in Fig. 3) has three concentric circles with diameters of 1, 3 and 6 mm, which correspond respectively to the anatomic fovea, parafoveal ring and perifoveal ring: the anatomic macula disk encompasses all three of these. Finally, on an HD 5 Line Raster (not shown in Fig. 3), the scan angle, line spacing and length are printed: the default values are zero degrees, 0.25 mm and 6 mm. The correlations between these OCT instruments compare favorably for normal eyes but they differ significantly for abnormal eyes. The two Zeiss instruments, Cirrus and Stratus, had a standard deviation of the mean difference between measurements of central macular subfield thickness of 20 µm [7]. A study of four different models of OCTs devices found an average difference in retinal thickness of 50 µm and a repeatability of 60 µm [8]. Our ophthalmologist feels that a 10% difference between images is noteworthy. This paragraph shows that there is variability within and between OCT instruments made by the same and different manufacturers. Therefore, it takes effort to discover what is being presented, before these results can be com
pared and contrasted.

The point of this section is that similar information about the retina can be obtained from many different instruments. Each instrument has a specific view of the retina. These views are not interchangeable.

3. Results

3.1 Putting Fundus Photo Information on a Visual Field Diagram

A lens flips an image horizontally and inverts it vertically. A fundus photo is taken by a camera looking into the eye and a visual field diagram is derived by the subject looking out of the eye. So to compare a visual field diagram with a fundus photo you must flip the image horizontally and invert it. To flip it horizontally you can move from a position in front of the subject to a position behind the subject. This is the 180º horizontal rotation. However, you did not stand on your head when you went behind the subject, so you must still invert the vertical aspect information.

When referring to a region of a photograph or a diagram we will use geometric descriptions, for example, the upper-right corner of the photograph. In contrast, when we are referring to anatomy or visual fields, we will use anatomical descriptions, such as the inferior-nasal portion of the left eye's field of view.

How would the scar tissue seen in Fig. 3 affect our subject's visual fields? A large area of scar tissue can be visualized in three images: (1) the upper-right corner of the OS OCT photo,(2) upper-right corner of the OS fundus photo and (3) corresponding lower-right corner of the left eye visual field diagram. Because of the properties of an ocular lens and a fundus camera, scar tissue in the upper-right corner of the fundus photo manifests as a scotoma in the lower-right corner of the visual field diagram. Therefore, when looking straight-ahead (primary position) with his left eye, our subject would not see objects in the inferior-nasal field of view, like a finger tapping his upper lip. Please note that the large white area in the OS OCT image is the area of greatest cystoid macular swelling, it is not the cause of the visual field defect. The cause of the visual field defect is the area of scar tissue that is in the upper-right corner of this image. The other area of scar tissue that is in the inferior-nasal part of the retina is not seen clearly in the photos of Fig. 3, and therefore it is not discussed here.

This paragraph describes the procedure that was used to overlay information from fundus photos and OCT images onto visual field diagrams to produce Fig. 4. First, we resized one of the images (either the fundus photo or the visual field) so that they had the same scale (degrees of visual angle per millimeter of display). To do this calibration, if we had a clear outline of the optic disk, then we assumed that it was 6.3 degrees in diameter. Otherwise, we assumed that the width of the central retinal artery was 166 ± 15 µm and the width of the central retinal vein was 246±18 µm [9], but these measures had a lot of variability. (Two regions of the central retinal vein are marked in figure 1.) Next, we flipped the fundus photo vertically and put the optic disk from the fundus photo on top of the blind spot in the visual field diagram. Then, to get the rotation correct, we put the fovea from the fundus photo on top of the fixation point (usually the center of the diagram) in the visual field diagram. This process is illustrated in Figs. 3 and 4.

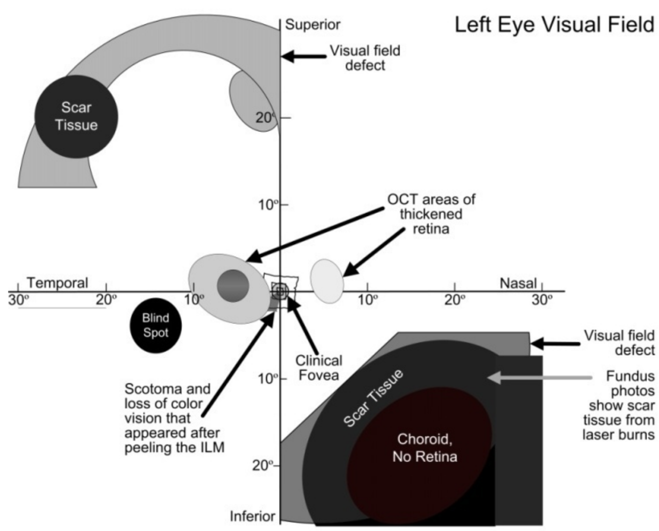


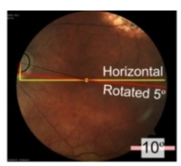
Fig. 4. A visual field diagram for the left eye with fundus photo and OCT information overlaid

If Photoshop or Visio are being used to illustrate the principle of a lens, then a vertical flip followed by a horizontal flip is equivalent to a 180-degree rotation.

3.2 Optomap Image of the Retina

Fig. 5 was designed to show the effects of cyclorotation: it has a traditional fundus photo (top) and an image from a new instrument called the Optomap (bottom), which will be discussed in our Wide-field Imagery section. In both of these images, if we assume that the eye is not cyclorotated, then the optic disk appears to be 15º nasal and 4º superior to the fovea. This vertical distance is larger than the normal 1.5º±0.9º. Therefore, we re-examined this fundus photo assuming that the eye was cyclorotated by 5º. (Because of his first detached retina operation, our subject has strabismus, which includes 5° excyclorotation [1].) Now, the optic disk appears to be 15.3º nasal and 2.7º superior to the fovea, which is closer to normal. Fundus photos, visual field diagrams and Optomap images all showed this same cyclorotation effect. This effect was not as prominent in OCT images, because the OCT fixation target was a ten-degree asterisk, which gave strong cyclorotation clues and presumably, the subject would suppress his cyclorotational tendency. All of these measurements were made without spectacles, with monocular viewing.

Technical note: Torsion produced by twisting a material in rotational motion is analogous to tension produced by stretching a material in linear motion. The torsional torque is proportional to the angle of rotation just as the tension force is proportional to the distance of extension. So, torsion is proportional to rotation, but torsion is not the same as rotation. However, in the ophthalmology literature cyclotorsion is synonymous with cyclorotation.



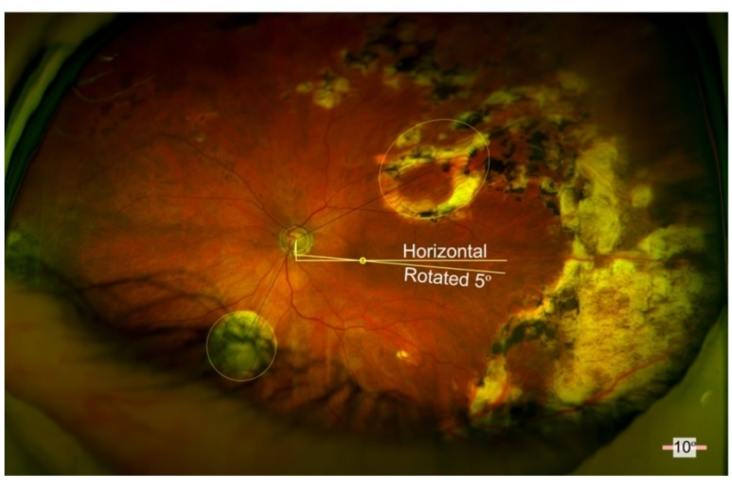


Fig. 5. Fundus photo (top) and Optomap image (bottom) of the left eye. Both pictures show the effects of cyclorotation of the eye. Circles surround the optic disk, the fovea and specific sections of scar tissue

This section has shown fundus photo information and OCT information being overlaid onto a visual field diagram. If we put this all together, we can show what we believe our subject sees with his left eye as illustrated with Fig. 4.

The macular scotoma of Fig. 2 cannot be seen in the fundus photos, the OCT images or even the Optomap images. However, in retrospect, we can see hints of this macular scotoma in some visual field diagrams, or perhaps it is just that we see what we believe.

3.2 Wide-field Imagery

We used a new instrument to image the retina, the Optomap®, which produces images similar to those of a fundus camera. The bottom of Fig. 5 shows an image computed by this instrument. Compared to fundus photographs, Optomap images (1) have a larger field of view, (2) show features in front of the eye, like eyelashes and eyelids, (3) have greater resolution of arteries and veins and (4) can show arteries and veins in the choroid. Information from these images can be superimposed on visual field diagrams the same as OCT and fundus photo information. However, the Optomap images are not linear, because they use a nonlinear transformation from a three-dimensional retina to a two-dimensional image. The differences are obvious in Fig.5. For both the top and the bottom photos, the size of the calibration bar in the lower-right corner and the size of the optic disk (which is located on the left edge of the fundus photo and in the center of the Optomap photo) are the same. However, the scar tissue on the upper-right margin of the fundus photo is shifted centrally in the Optomap photo. An object that would be “around the backside” of the fundus photo is displayed centrally in the Optomap photo.

The fields of view of our Optomap images were about 25 optic disk diameters horizontally and 13 disk diameters vertically. Assuming the diameter of the optic disk is six degrees, this gives a field of view of 150º by 80º. Three images of normal subjects from the Optos website had fields of view, on average, of 23 disk diameters horizontally and 17 disk diameters vertically, which gives a field of view of 140º by 100º. So we believe that the field of view of the Optomap is around 150° by 90°, which is smaller than the marketing claims.

Fig. 5 shows an Optomap image of the left eye and its retina (bottom part of the figure). The unrealistic colors result from using only two scanning lasers: a green laser with a 532 nm wavelength and red laser at 633 nm. The Optomap image shows the optic disk and blood vessels radiating from it. The lower eyelid with its eyelashes is on the top of the image and (because there is an inverting lens between the front of the eye and the retina) the superior part of the retina is also on the top of the image. This left eye image shows scar tissue caused by the laser photocoagulation and cryopexy freezing procedures. In the upper right part of this image, there is a ring of scar tissue about 20º in diameter. Inside of this ring, there is no retina: therefore, the eight wavy red lines are choroid blood vessels. So the Optomap instrument produces photographs that are similar but different from fundus photos. These instruments would be used for different purposes.

3.3 Comparison of Retina-Visualizing Techniques

Table 2 is a cursory comparison of the retina-visualizing techniques that were discussed in this paper. The numbers are subjective. For example, there are many manufactures of fundus cameras: most of them have different fields of view and resolutions. You can use them with or without pupil dilation. Older ones did not produce digital images, some newer ones do. Patents on aspects of fundus cameras run back into the 1920s.

Table 2. Qualitative evaluation of some retina-visualizing techniques

Instrument→ Metric ↓	**Subject-reported vision**	**Ophthalmo-scope**	**Slit lamp**	**Fundus camera**	**OCT**	**Optomap**
Invented	a long time ago	1850	1920s	1950s	1990s	2000s
Typical field of view	150º Horz by 135º Vert	20º	2º by 60º	30º to 50º	40º	150º Horz by 80º Vert
Produces digital image	no	no	yes	yes	yes	yes
Produces true color image	yes	yes	yes	yes	no	no
Linear	yes	yes	yes	weakly	claims to be	no
The next four rows use a 0 to 10 scale where 10 is the best.						
Resolution	10	4	6	7	8	9
Usefulness	2	3	6	6	8	9
Patient comfort (without pupil dilation)	10	4	6	7	8	8
Patient comfort (with dilation). Patients dislike dilation and its effects.	not applicable	3	2	4	5	5

The last four rows of Table 2 and all of numbers in Table 3 are subjective. They were established in multiple iterative discussions between the two authors. Barry has all of these instruments in his office and he has made extensive use of each. Other evaluators could easily give different numbers, but we think that the trends would be the same.

Table 3 shows which techniques can evaluate which symptoms. Bahill and Barry [1] give a detailed explanation of each of these symptoms. The right column, doctor's exam, means his or her summary after talking with the patient and reviewing all of the patient's record. The doctor's diagnosis and prognosis could be flawed due to lack of time, lack of documented processes, incorrect test results, failure to notice information, lack of knowledge, poor decision-making, mistakes and different nomenclature. Therefore, the doctor's report could be better or worse than any instrument.

Table 3. Which viewing techniques detect and evaluate which symptoms?

The scale goes from1 to 10, with a 10 indicating the best detectability for each symptom. Blank cells are zeroes.

Techniques→ **Symptoms ↓**	**Subjects report**	**Ophthalmoscope**	**Slit lamp**	**Fundus camera**	**OCT**	**Optomap**	**Snellen chart**	**Fluorescein angiography**	**Visual fields test***	**Phoropter**	**Doctors exam**
Pain in the eye	10										4
Pain in the brain	10										1
Poor visual acuity due to wrinkled retina	10 Fig. 2	2	3	4	3	5	2	5	5	7	8
peripheral scar tissue	7	8	5	10 Fig. 3	9 Fig. 3	10 Fig. 5		8	9 Figs. 3 & 4		9
macular scars and holes	9	6	4	8	8	8	7	6	4		7
foveal scotoma	10 Fig. 2						4	2			1
retinal edema	1	3	4	4	10 Fig. 3	5	5	7	5	9	9
macular edema	1	3	3	2	10	6	2	3	3	5	9
color blindness	8										4
Left eye misalignment (phoria)	10									8	9
Double vision (diplopia)	10									8	9
Lack of depth perception (no stereopsis)	9										1
Non-circular and non-responsive (tonic) pupil	5		5								9
Light sensitivity	8	5	5	3							6

*A Macular 10-2 Threshold visual fields test would do better.

In the future, ophthalmological instrument manufacturers will probably add software programs so that their medical instruments can measure more and more of the symptoms in Table 3. For example, the manufacturer could easily add a program to the Optomap so that it could detect non-circular or non-responsive pupils.

Table 3 shows that each technique is best for a different symptom: we were surprised at the small overlap. These dozen symptoms seemed like a dozen different problems. But now we can understand the relationships between these problems. We can understand this medical history as one system, instead of a dozen isolated events. Table 4 shows how treating one symptom affects other symptoms. Tables 3 and 4 and Figs. 3 and 4 brought it all together as one system, instead of a dozen unrelated symptoms. For years, we had a dozen doctors and a dozen symptoms: each doctor treated his most familiar symptoms, one at a time, with his most familiar retina-viewing techniques. Face-to-face communication between the ophthalmologists and optometrists would have led to an earlier understanding of this system. If we had understood this system years ago, might the treatment have been different? The patient's eye is a system: it is not a collection of a dozen contradictory symptoms and measures.

Table 4. Systems analysis of this case study

The event in this column	Prompted the action in this column	Which resulted in the outcome in this column	This later ameliorating action	Produced this final outcome
Cataract growth	original cataract operation	pain in the front of the eye	Replacing the intraocular lens (IOL)	eliminated pain in the iris
"	original cataract operation	light sensitivity and a non-circular, non-responsive (tonic) pupil	none is known	permanent damage to iris
Retinal detachment (probably precipitated by the cataract operation.)	many retina operations	macular edema	Peeling the ILM	foveal scotoma, color blindness. wrinkled retina and poor visual acuity.
"	implanting a scleral buckle	inflammation and pain on the back of the eye	Removing exposed sutures on the back of the eye	eliminated pain on the back of the eye
"	implanting a scleral buckle	phoria, diplopia and pain in the brain	Prescribing spectacles with prisms	reduced the pain in the brain
"	implanting a scleral buckle	cyclorotation in rest position causing pain in the brain	none is known	pain in the brain

4. CONCLUSION

Fig. 1 and Table 1 were presented to clarify some very confusing nomenclature that exists in the retina literature: this table has no internal contradictions. Fig. 3 and Table 2 showed the relationships between subject-reported vision, a view through an ophthalmoscope, a view through a slit lamp, a photograph of a face, optical coherence tomography (OCT) images, fundus photos, visual field diagrams and Optomap images, all on oneunique subject: the subject is unique and the analysis is original. Finally, Tables 3 and 4 showed that the subject's dozen different symptoms were only parts of one system.

CONSENT

The patient has given his informed consent for this report to be published.

ETHICAL APPROVAL

All authors hereby declare that all experiments have been examined and approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

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BIOGRAPHICAL SKETCHES

Terry Bahill is an Emeritus Professor of Systems Engineering and of Biomedical Engineering at the University of Arizona in Tucson. He received his Ph.D. in electrical engineering and computer science from the University of California, Berkeley, in 1975. Bahill has worked with dozens of high-tech companies presenting seminars on Systems Engineering, working on system development teams and helping them to describe their Systems Engineering processes. He holds a U.S. patent for the Bat Chooser, a system that computes the Ideal Bat Weight for individual baseball and softball batters. He was elected to the Omega Alpha Association: the Systems Engineering Honor Society. He received the Sandia National Laboratories Gold President's Quality Award. He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), of Raytheon Missile Systems, of the International Council on Systems Engineering (INCOSE) and of the American Association for the Advancement of Science (AAAS). He is the Founding Chair Emeritus of the INCOSE Fellows Selection Committee. His picture is in the Baseball Hall of Fame's exhibition "Baseball as America." You can view this picture at http://www.sie.arizona.edu/sysengr/.

Patrick J. Barry earned his BS at Siena College in Loudenville, NY, with a major in biology and a minor in chemistry. He earned a Doctor of Optometry Degree from the Pennsylvania College of Optometry in 1977 and has been in private practice since 1989, providing primary care Optometric services to the Tucson community. Dr. Barry is a member of the American Optometric Association, the Arizona Optometric Association and the Southern Arizona Optometric Society. He is a Past- President of both the Southern Arizona Optometric Society and the Arizona Optometric Association, where he received the prestigious Optometrist of the Year Award for his dedication to the Optometric profession. envisioneyecarecenter@gmail.com

COMPETING INTERESTS

Neither author has any conflicts of interest with regards to this paper: furthermore, we believe that there is nothing that could be construed as a conflict of interest. This research was not funded by any organization.

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