

Multimodal Views of the Human Retina

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ABSTRACT

Aims: To show the relationships between subject-reported measures of vision, the view through an ophthalmoscope, the view through a slit lamp, a photograph of a face, 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 was put into the figures of 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 further shows 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. Then 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 nonlinear and are different for different techniques.

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21 **Keywords:** retina imaging; OCT; fundus photograph,

22 1. INTRODUCTION

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

32 Our subject, A. Terry Bahill (ATB), has had a dozen eye surgeries over the last half-dozen
33 years. He has been examined and treated by an optometrist, ten ophthalmologists, et al.
34 Over 1000 clinical ocular measurements have been performed on his eyes using various
35 retina viewing techniques [1] [Bahill and Barry, 2013]. These data were analyzed,
36 summarized and reduced to 50 images and tables: these data were categorized, filtered and
37 the essence was put into the figures of this paper. Our objective was to show (in layman's
38 terms) the relationships between the following views of the human retina: through the
39 subject's eye, through an ophthalmoscope, through a slit lamp, through the clinician's eye
40 looking at a face, fundus photos, optical coherence tomography images, visual field
41 diagrams and Optomap images.

42 1.1 Assumptions

43 One millimeter on the human adult retina corresponds to 3.5° of visual angle (0.286 mm/deg)
44 (with a range of 3.4° to 3.6°). The optic disk (the image of the optic nerve and blood vessels
45 entering and leaving the retina) can be modeled as a disk with a diameter of 6.3° (1.8 mm ±
46 0.3). A more complex model is that of an ellipse 6.1° (1.75 mm) wide and 6.5° (1.85 mm)
47 high. On the retina, the center of the optic disk is 15.5° ±1.1° (4.4 mm) nasal and 1.5° ±0.9°
48 (0.4 mm) superior to the center of the fovea [2, 3] [Rohrschneider 2004; Kolb 2013]. As long
49 ago as 1867 Hulke [4] wrote, "I found the distance of the fovea from the centre of the optic

50 nerve exactly equalled [sic] $1\frac{5}{6}$ ". The triple prime symbol stands for ligne, which equals

51 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

52 is within one standard deviation of the diameter given above.

53 1.2 Names of Retina Areas

54 Different classes of people (e.g. clinicians [like optometrists and ophthalmologists],
55 anatomists, engineers, etc.) have named the areas of the retina differently [5] [Park, 2006].
56 This has created confusion. Therefore, we created Table 1 and Figure 1 to unravel this
57 muddle.

58 **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, 0°	Center of fovea	Umbo	
Floor of foveal	0.29 mm, 1°	Fovea , fovea	Foveola	It has red and green cones, but

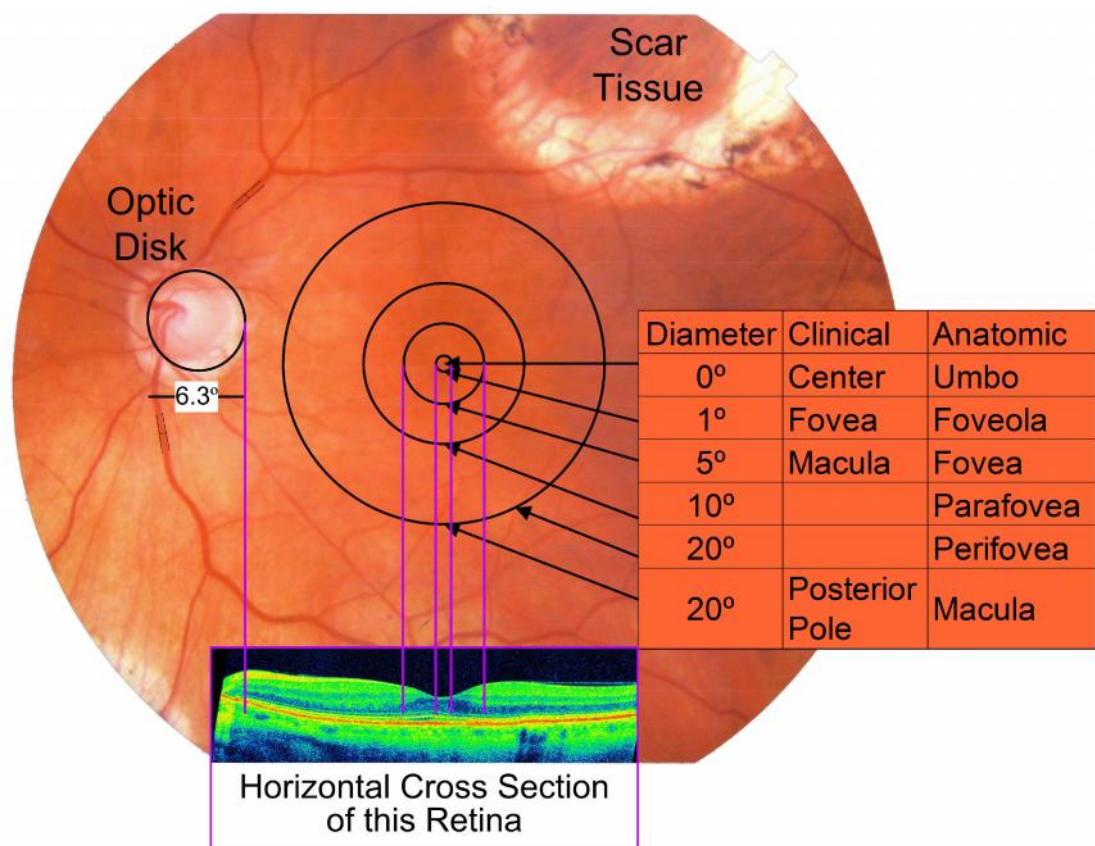
pit		centralis[4] [Hulke, 1867]		no blue cones, no rods and no vasculature
Capillary free zone	0.6 mm, 2°	Foveal avascular zone	Foveal avascular zone	It has no arterioles or venules. It is not circular.
Sloping sides of the foveal pit	1.4 mm, 5°	Macula , macula lutea, yellow spot [4] [Hulke, 1867]	Fovea , fovea centralis	It is the darkly pigmented <i>disk</i> 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, 10°		Parafovea	Its ganglion cell layer is composed of four to seven rows of cells.
Ring around parafovea	5.7 mm, 20 °		Perifovea	Its ganglion cell layer contains two or three rows of cells.
Disk containing all of the above	5.7 mm, 20°	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 1.8 mm (6.3 °) in diameter. When a typical person is viewing a scene, the classic fovea is the size of their little fingernail at arm's length.				

59 Column 3 of Table 1 is the classic (or clinical or traditional) retina nomenclature, which goes
60 back at least one hundred and fifty years [4] [Hulke, 1867]. Column 4 is the anatomic (or
61 histologic) nomenclature. Dictionaries and encyclopedias usually give the clinical
62 nomenclature. Research papers usually use the anatomic nomenclature. For the last two
63 centuries, the clinical macula (the darkly pigmented 5° disk in the center of the retina) has
64 been called the yellow spot or the macula lutea [4] [Hulke, 1867]. With red-free light or
65 certain preparations it may appear yellow; however, in a fundus photos, it looks dark red. A
66 large number of papers describe the macula lutea as a 5° oval-shaped yellow spot in the
67 center of the retina and then they proceed to show a fundus photo with a 5° dark red disk
68 marked as the macula. The Cirrus OCT macular cube ILM-RPE thickness box has three
69 concentric circles with diameters of 1, 3 and 6 mm, which correspond respectively to the
70 anatomic fovea, parafoveal ring and perifoveal ring: the anatomic macula disk encompasses
71 all three of these.

72 The foveal pit is a depression in the center of the retina. It was not a popular landmark until
73 cross sectional views of the retina became common. Now it is a clearly defined landmark. It
74 is easy to measure the rim-to-rim distance of the foveal pit, 1.85 ±0.23 mm [6] [DuBois,
75 2012]. This number is also being given here to show that the inter subject variability of these
76 metrics is large.

77 Figure 1 shows a fundus photo of the retina of the left eye. It has an arc of scar tissue
78 (created by a laser in order to reattach a detached retina) in the upper right corner of the
79 retina and a small area of scar tissue in the lower left corner. The optic disk is circled.
80 Because the subject was myopic there is a sclera crescent of white outside of the optic disk.
81 The circles in the center show the regions of the retina that are named. The rectangular inset
82 at the bottom is a horizontal cross section of the retina, a slice right through the center of the

83 fovea. On the left side of this rectangle the surface of the retina starts to dip down into the
84 optic disk.



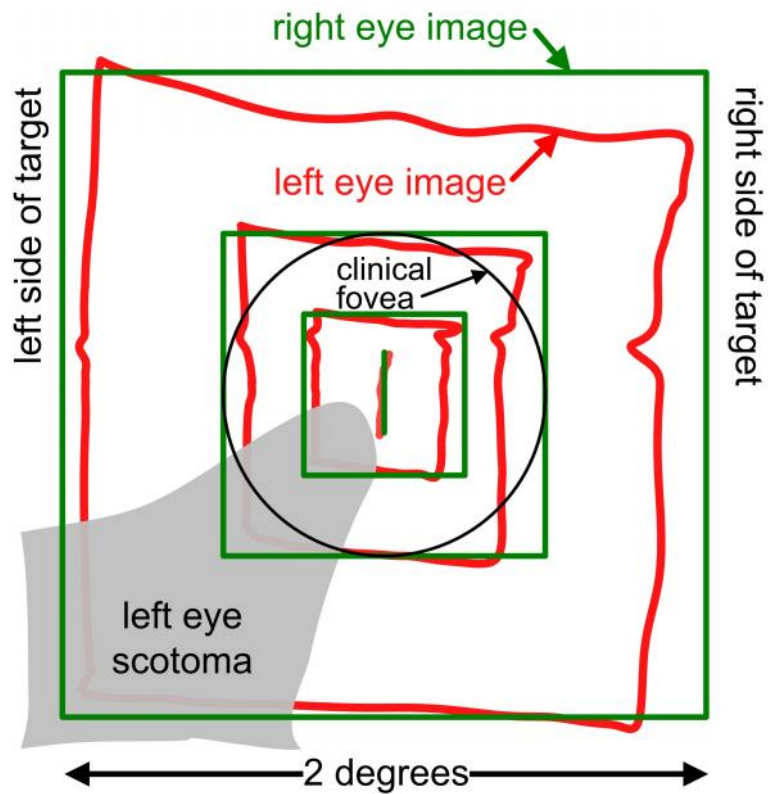
85
86 **Fig. 1. Names for areas of the retina.**

87 **2. METHODS**

88 **2.1 Seeing the Retina**

89 In this paper, we will consider the following techniques for *seeing* a person's retina: subject-
90 reported vision, an ophthalmoscope, a slit lamp, fundus photos, Optical Coherence
91 Tomography (OCT), visual field diagrams and the Optomap instrument. First, in Figure 2, we
92 show the subject's reported vision of a black-line target composed of concentric squares.
93 The right eye's image (thin green lines) is the same as the visual target. The left eye's image
94 (thick red lines) shows the distortion due to a wrinkled retina (macular pucker). The scotoma
95 in the lower-left quadrant probably resulted from peeling the inner limiting membrane (ILM).
96 Deriving this figure was complex and time consuming. This figure is the result of dozens of
97 measurements taken over several years. None of our other retina viewing techniques give
98 resolution this fine.

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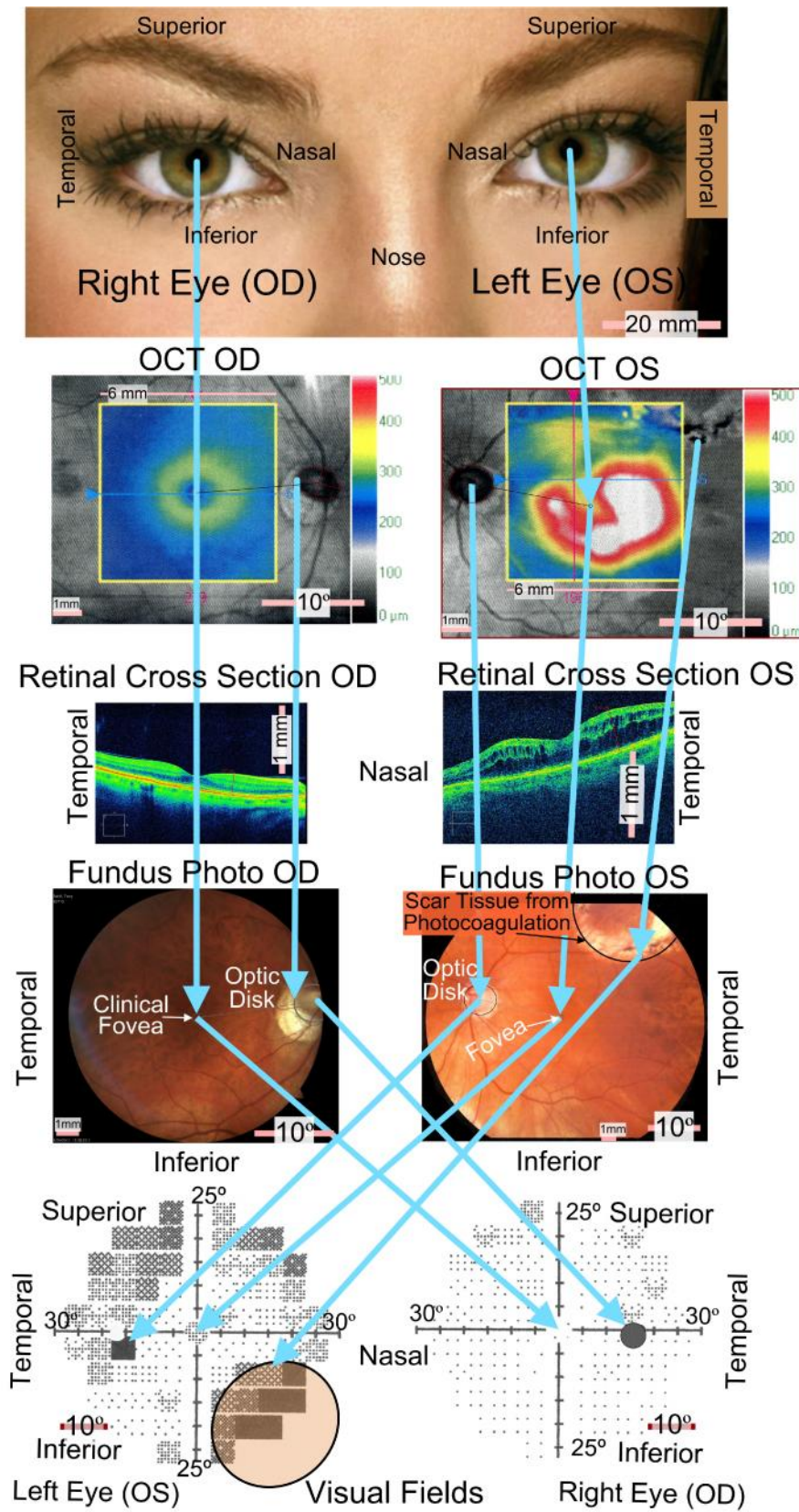


99
100
101

Fig. 2. The subject's viewpoint of a black-line target composed of concentric squares.

102 Next, in Figure 3, we compare several other techniques for evaluating the anatomy and
103 physiology of the retina. The clinician's view of the subject's face is shown in the top row of
104 Figure 3. The image of the subject's right eye (OD) is on the left side of the figure, the
105 subject's nose is in the middle of the figure, and the image of the subject's left eye (OS) is on
106 the right side of the figure. With the exception of this top row in Figure 3, all of the data in this
107 paper are for one subject, ATB. Figure 3 shows, from top to bottom, the clinician's view of
108 the subject's face, OCT images of the right and left retinas, horizontal cross sections of the
109 retinas, fundus photos of the retinas and visual fields for the left and right eyes. For each
110 row, the nasal sides of the eyes nose is are in the middle and the temporal sides of the eyes
111 temples are on the outside. Each column of Figure 3 has the foveae roughly aligned. The big
112 blue arrows show corresponding locations in the different diagrams. For the right eye, the
113 blue alignment arrow connects the temporal edges of the optic disk in the OCT image and in
114 the fundus photo: this is meant to draw attention to the edge of the fovea in the cross section
115 of the retina. For the left eye, this arrow connects, more naturally, the centers of the optic
116 disks. The blue arrows show corresponding locations. Significant points were lined up as
117 well as possible. However, a perfect mapping is impossible: because (among other reasons)
118 the algorithms for transforming three-dimensional (3D) space into two-dimensional (2D)
119 images are nonlinear and are different for different techniques¹. Furthermore, the
120 magnification scales are different for each diagram in this figure.

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 is the Mercator projection. Google Earth uses a Simple Cylindrical projection. Each of these ophthalmic instruments uses some algorithmic projection, but we do not know which algorithm is used by which instrument.



122 **Fig. 3. Shown from top to bottom are the clinician's view of the subject's face, OCT**
123 **images of the right and left retinas, cross sections of the retinas, fundus photos of the**
124 **retinas and visual fields for the left and right eyes. Note the different scale for each**
125 **row.**

126 **2.2 Fundus Photos**

127 The fourth row of Figure 3 shows fundus photos of our subject's right and left retinas. A
128 fundus camera is designed to photograph the interior surface of the eye, including the retina,
129 optic disc, blood vessels, macula and fundus. Using optical lenses it produces an upright
130 image of the retina. These images are displayed from the viewpoint of the clinician looking
131 into the subject's face. Therefore, objects that are anatomically in the top part of the retina
132 will appear in the top of the fundus photo. Objects in the nasal part of the retina will appear in
133 the nasal part of the fundus photo. In rows two and four of Figure 3, the ugly ring in the
134 superior-temporal region of the left eye's fundus photo and OCT image is scar tissue caused
135 by laser photocoagulation. Because this subject was myopic, the optic disk has a white
136 crescent around it, which is prominent in the right eye. On fundus photos, arteries are lighter,
137 smaller and less tortuous than veins.

138 **2.3 Visual Field Diagrams**

139 Visual field diagrams show what the subject sees when looking forward out of one eye or the
140 other (monocular viewing). Visual field diagrams are printed from the viewpoint of the subject
141 looking out. This causes a 180° horizontal rotation from the fundus photos. The visual field
142 diagrams of the two eyes are usually plotted side by side, with the left eye on the left of the
143 diagram and the right eye on the right of the diagram, as in the fifth row of Figure 3. This
144 puts the temporal parts of the visual fields on the sides of the diagram (near the temples)
145 and the nasal parts in the middle. Things that are in the top part of the visual field will appear
146 in the top of the visual field diagram. Anatomically, the center of the optic nerve (the blind
147 spot) is on average 15.5° nasal and 1.5° superior to the center of the fovea. So visually, the
148 blind spot will be about 15.5° temporal of the center of the fovea as indicated with the solid
149 black circles. The dark squares are areas where the subject does not see. The large dark
150 area in the inferior-nasal region of the left eye's visual field corresponds to the scar tissue in
151 the superior-temporal region of the left eye's fundus photo. In contrast to the other retina
152 viewing techniques, a visual field plot is linear, because the targets are projected onto a
153 horopter screen (roughly speaking, a section of a sphere.)

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

160 **2.4 OCT Images**

161 Optical Coherence Tomography (OCT) images follow the display conventions previously
162 described for fundus photos. An OCT instrument images the retina by measuring the echo
163 time delay and magnitude of backscattered or back-reflected light. ~~It uses an interferometer,~~
164 ~~where a beam of broadband, low-coherence light from a super-luminescent light-emitting~~
165 ~~diode that is directed~~ It directs a beam of light through a beam splitter or fiber coupler. One
166 beam is focused on the subject's retina, and the other is directed at a reference mirror. Light
167 from the incident beam is reflected off retinal structures at different axial depths and merged
168 with light reflected from the reference mirror. All of this information is put into a three
169 dimensional model in the computer. This model can then be enlarged, rotated, sectioned,
170 etc.

171 The OCT diagrams in the second row of Figure 3 show the optic disk and blood vessels
172 radiating from it on the nasal edge for both eyes. The superimposed central square shows
173 (with a color code) the thickness of the retina (specifically the distance between the ILM and
174 the Retina Pigment Epithelium (RPE)). The intersections of the red and blue hairlines in the
175 second row indicate the centers of the foveae, as determined by the computer: for the left
176 eye, this point is wrong, probably because the instrument defines the fovea as the area
177 where the retina is the thinnest and this eye's retinal thickness is altered by edema. Next,
178 row 3 of Figure 3 shows a horizontal cross section of the retina passing through the fovea.
179 For the OS there is fluid (macular edema) under the retina: this appears as black columns
180 above the yellow RPE line.

181 We have used three different OCT systems: Heidelberg Engineering, the Optos Optomap
182 and Zeiss Cirrus. The following describes the calibration measures for the Zeiss Cirrus OCT.
183 In a Macular Cube 512 x 128 diagram (second row of Figure 3), the ILM-RPE box overlaid
184 on the fundus photo is 6 by 6 mm. The ILM-RPE thickness box (not shown in Figure 3) has
185 three concentric circles with diameters of 1, 3 and 6 mm, which correspond respectively to
186 the anatomic fovea, parafoveal ring and perifoveal ring: the anatomic macula disk
187 encompasses all three of these. Finally, on an HD 5 Line Raster (not shown in Figure 3), the
188 scan angle, line spacing and length are printed: the default values are 0°, 0.25 mm and 6
189 mm. The correlations between these OCT instruments compare favorably for normal eyes
190 but they differ significantly for abnormal eyes. The two Zeiss instruments, Cirrus and Stratus,
191 had a standard deviation of the mean difference between measurements of central macular
192 subfield thickness of 20 μm [7] [Lammer, et al., 2011]. Our ophthalmologist feels that a 10%
193 difference between images is noteworthy. A study of four different models of OCTs devices
194 found an average difference in retinal thickness of 50 μm and a repeatability of 60 μm [8]
195 [Giammaria, et al., 2011]. The point of this discussion is that similar information about the
196 retina can be obtained from many different instruments. With sufficient effort to discover
197 what is being presented, this information can be compared and contrasted. However, there
198 is variability within and between the instruments. Each has a specific view of the retina. They
199 are not interchangeable.

200 3. RESULTS

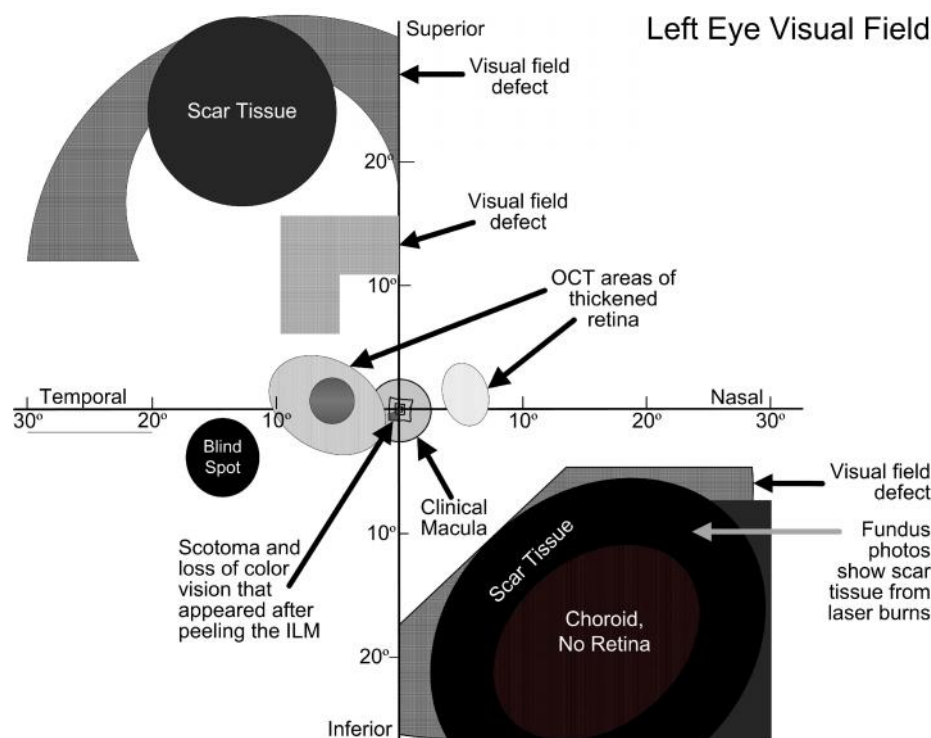
201 3.1 Putting Fundus Photo Information on a Visual Field Diagram

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

209 How would the scar tissue seen in Figure 3 affect our subject's visual fields? A large area of
210 scar tissue can be seen in three images: (1) the upper-right corner of the OS OCT photo, (2)
211 upper-right corner of the OS fundus photo and (3) corresponding lower-right corner of the left
212 eye visual field. Because of the properties of an ocular lens and a fundus camera, scar
213 tissue in the superior-temporal region of a fundus photo manifests as a scotoma in the
214 inferior-nasal region of the visual field diagram. Therefore, when looking straight ahead
215 (primary position) with his left eye, our subject would not see objects in the lower-right field
216 of view, like a finger tapping his upper lip. Please note that the large white area in the OS
217 OCT image is the area of greatest cystoid macular swelling, it not the cause of the visual
218 field defect. The cause of the visual field defect is the area of scar tissue that is in the upper-
219 right corner of this image.

220 The following section describes the procedure that was used to overlay information from
 221 fundus photos and OCT images onto visual field diagrams to produce Figure 4. First, we
 222 resized one of the images (fundus photo or visual field) so that they had the same scale
 223 (degrees of visual angle per millimeter of display). To do the calibration, if we had a clear
 224 outline of the optic disk, then we assumed that it was 6.3 degrees in diameter. Otherwise, we
 225 assumed that the width of the central retinal artery was $166 \pm 15 \mu\text{m}$ and the width of the
 226 central retinal vein was $246 \pm 18 \mu\text{m}$ [9] [Taarnhøj, 2006], but these measures had a lot of
 227 variability. (Two regions of the central retinal vein are marked in Figure 1.) Next, we flipped
 228 the fundus photo vertically and put the optic disk from the fundus photo on top of the blind
 229 spot in the visual field diagram. Then, to get the rotation correct, we put the fovea from the
 230 fundus photo on top of the fixation point (usually the center of the diagram) in the visual field
 231 diagram. This process is illustrated in Figures 3 and 4.

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



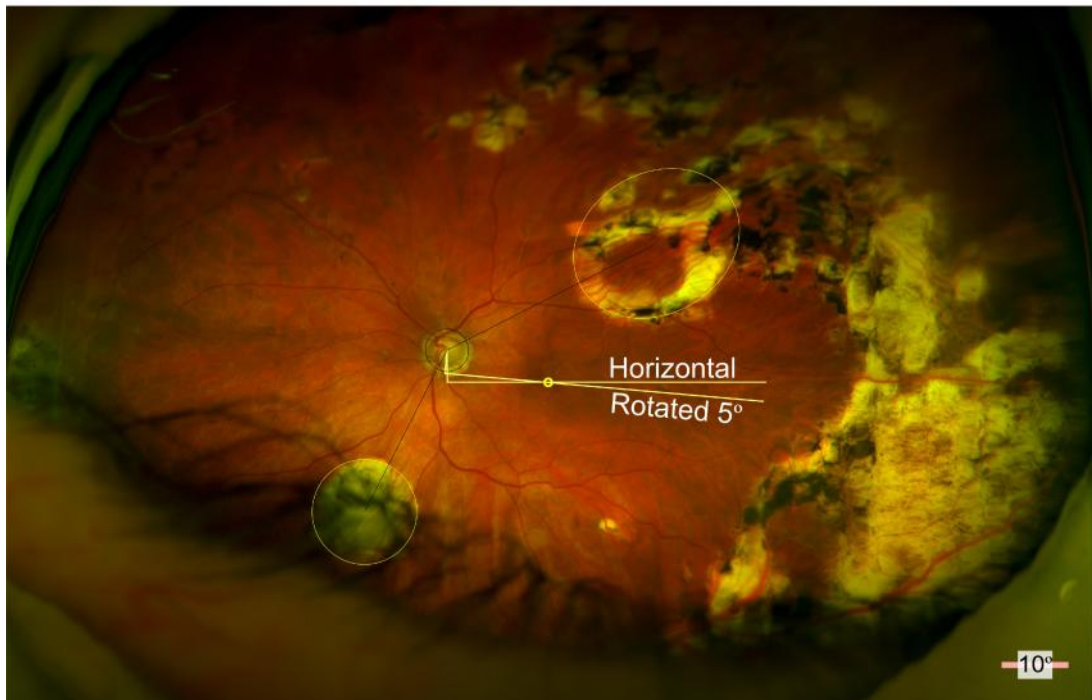
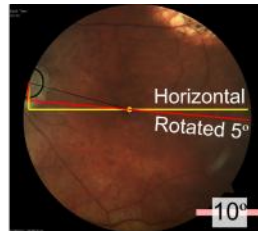
234
 235 **Fig. 4. A visual field diagram for the left eye with fundus photo and OCT information**
 236 **overlaid.**

237 3.2 Optos image of the same scar tissue

238 Figure 5 was designed to show the effects of cyclorotation: it has a traditional fundus photo
 239 (top) and an image from a new instrument called the Optomap (bottom), which will be
 240 discussed in our Wide-field Imagery section. In both of these images, if we assume that the
 241 eye is not rotated, then the optic disk appears to be 15° nasal and 4° superior to the fovea.
 242 This vertical distance is larger than the normal $1.5^\circ \pm 0.9^\circ$. Therefore, we re-examined this
 243 fundus photo assuming that the eye was cyclorotated by 5° . Now, the optic disk appears to
 244 be 15.3° nasal and 2.7° superior to the fovea, which is closer to normal. Fundus photos,

245 visual field diagrams and Optomap images all showed this same cyclorotation effect. This
246 effect was not as prominent in OCT images, because the OCT fixation target was a ten-
247 degree asterisk, which gave cyclorotation clues. All of these measurements were made
248 without spectacles, with monocular viewing.

249



250

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

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

257 The macular scotoma of Figure 2 cannot be seen in the fundus photos or the OCT images.
258 However, in retrospect, we can see hints of this macular scotoma in many visual field
259 diagrams like those of Figure, or perhaps it is just that we see what we believe.

260 3.2 Wide-field Imagery

261 We used a new instrument to image the retina, the Optomap®, which produces images
262 similar to those of a fundus camera. The bottom of Figure 5 shows an image computed by
263 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. We do not know how this transformation compares to those of fundus photos and OCT images.

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 150° by 80°. 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: this gives a field of view of 140° by 100°.

Figure 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 20° in diameter. Inside of this ring, there is no retina: therefore, the eight wavy red lines are choroid blood vessels.

3.3 Comparison of Techniques

Table 2 is a cursory comparison of the retina viewing techniques that were discussed in this paper. Of course, the numbers are just suggestive. 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 viewing techniques

Instrument→ Metric ↓	Subject- reported vision	Ophthalmo- scope	Slit lamp	Fundus camera	OCT	Optomap
Invented	a million years a long time ago	1850	1920s	1950s	1990s	2000s
Typical field of view	150° Horz by 135° Vert	20°	2° by 60°	30° to 50°	40°	150° Horz by 80° 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
Binocular, can it evaluate both eyes at the same time	yes	no	yes	no	no	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 purely subjective. They were established in multiple 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] [2013] 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. 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 from 1 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	3	4	6	5	8	4	6	7	9	9
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						5	2			
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										5
Left eye misalignment (phoria)	10									8	9
Double vision (diplopia)	10									8	9

Lack of depth perception (no stereopsis)	9										
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.											

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

308 As can be seen in Table 3, each technique primarily illuminates a different symptom. We
309 were surprised at the lack of overlap. These dozen symptoms seemed like a dozen different
310 problems. This is like the story of seven blind men describing an elephant: each had a
311 different view. But now we can understand the relationships between these problems. We
312 can understand this medical history as a system, instead of a dozen isolated events. Table 4
313 shows how treating one symptom affects other symptoms. Tables 3 and 4 and Figure 3
314 brought it all together as one system, instead of a dozen unrelated symptoms. For years, we
315 had a dozen doctors and a dozen symptoms: each doctor treated his most familiar
316 symptoms, one at a time, with his most familiar retina viewing techniques. This shows the
317 need for face-to-face communication between the ophthalmologists and optometrists. If we
318 had understood this *system* years ago, the treatment would surely have been different. The
319 patient's eye is a system: it is not a collection of a dozen contradictory symptoms and
320 measures.

321 **Table 4. Systems analysis of this case study**

The event in this column	prompted the action in this column,	which produced 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 from the exposed sutures
	implanting a scleral buckle	phoria, diplopia and pain in the brain	prescribing spectacles with prisms	reduced the brain pain

322

323 **4. CONCLUSION**

324 Figure 1 and Table 1 have clarified some very confusing nomenclature that exists in the
325 retina literature: this table has no internal contradictions. Figure 3 and Table 2 have
326 explained the relationships between subject-reported vision, a view through an
327 ophthalmoscope, a view through a slit lamp, a photograph of a face, optical coherence
328 tomography (OCT) images, fundus photos, visual field diagrams and Optomap images all on
329 one unique subject: the subject is unique and the analysis is original. Finally, Tables 3 and 4
330 showed how the subject's dozen different symptoms were really only parts of *one system*.

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334 **COMPETING INTERESTS**

335 Neither author has any conflicts of interest with regards to this paper: furthermore, we
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338 **AUTHORS' CONTRIBUTIONS**

339 Bahill designed the study, performed the statistical analysis, wrote the protocol, and wrote
340 the first draft of the manuscript. Barry provided the medical instruments, measurements,
341 clinical images, and medical expertise.

342 **CONSENT**

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

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374 ACRONYMS

375	HD	High Definition
376	ILM	Inner Limiting Membrane
377	OCT	Optical Coherence Tomography
378	OS	Left eye
379	OD	Right eye
380	RPE	Retina Pigment Epithelium

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