Multimodal imaging of experimental choroidal neovascularization

Ioanna Tsioti¹, Xuan Liu¹,², Petra Schwarzer¹, Martin S. Zinkernagel¹, Despina Kokona¹

¹Department of Ophthalmology, Inselspital, Bern University Hospital, and Department of BioMedical Research, University of Bern, Bern 3010, Switzerland
²Department of Ophthalmology, the First Affiliated Hospital of Xi’an Jiaotong University, Xi’an 710061, Shaanxi Province, China

Co-first authors: Ioanna Tsioti and Xuan Liu

Correspondence to: Despina Kokona. Department of Ophthalmology, Inselspital, Bern University Hospital, Freiburgstrasse 4, Bern 3010, Switzerland. despina.kokona@insel.ch

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Abstract

● AIM: To compare choroidal neovascularization (CNV) lesion measurements obtained by in vivo imaging modalities, with whole mount histological preparations stained with isolectin GS-IB4, using a murine laser-induced CNV model.

● METHODS: B6N.Cg-Tg(Csf1r-EGFP)1Hume/J heterozygous adult mice were subjected to laser-induced CNV and were monitored by fluorescein angiography (FA), multicolor (MC) fundus imaging and optical coherence tomography angiography (OCTA) at day 14 after CNV induction. Choroidal-retinal pigment epithelium (RPE) whole mounts were prepared at the end of the experiment and were stained with isolectin GS-IB4. CNV areas were measured in all different imaging modalities at day 14 after CNV from three independent raters and were compared to choroidal-RPE whole mounts. Intraclass correlation coefficient (ICC) type 2 (2-way random model) and its 95% confidence intervals (CI) were calculated to measure the correlation between different raters’ measurements. Spearman’s rank correlation coefficient (Spearman’s r) was calculated for the comparison between FA, MC and OCTA data and histology data.

● RESULTS: FA (early and late) and MC correlates well with the CNV measurements ex vivo with FA having slightly better correlation than MC (FA early Spearman’s r=0.7642, FA late Spearman’s r=0.7097, and MC Spearman’s r=0.7418), while the interobserver reliability was good for both techniques (FA early ICC=0.976, FA late ICC=0.964, and MC ICC=0.846). In contrast, OCTA showed a poor correlation with ex vivo measurements (Spearman’s r=0.05716) and high variability between different raters (ICC=0.603).

● CONCLUSION: This study suggests that FA and MC imaging could be used for the evaluation of CNV areas in vivo while caution must be taken and comparison studies should be performed when OCTA is employed as a CNV monitoring tool in small rodents.

● KEYWORDS: choroidal neovascularization; in vivo imaging; fluorescein angiography; multicolor fundus imaging; optical coherence tomography angiography

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INTRODUCTION

Exudative (wet) age-related macular degeneration (wAMD) is one of the most common retinal diseases that causes visual impairment and blindness in the elderly population[1-2]. The formation of new abnormal blood vessels beneath the retina and into the choroid is the main characteristic of the disease[3]. Laser-induced choroidal neovascularization (CNV) is used as an experimental model of AMD in rodents and it relies on the rupture of Bruch’s membrane and subsequent neovascularization, similar to that seen in human AMD where new choroidal vessels migrate spontaneously into the sub-retinal pigment epithelium (RPE) or sub-retinal space[4]. This model can be utilized for the evaluation of treatment approaches as well as for the investigation of the disease pathophysiology in small animals. However, for several reasons, in vivo monitoring of CNV lesions overtime would be beneficial. Until today, the gold standard for CNV lesion measurements in rodents relies on histological preparations. Yet, histology requires euthanasia of the animal and cannot be used for longitudinal studies. In the clinical practice imaging modalities such as fluorescein angiography (FA), multicolor (MC) fundus imaging and optical coherence tomography angiography (OCTA), are used as diagnostic tools of retinal impairments, providing important information about the disease outcome[5].
More recently, FA and OCTA have been utilized in experimental models of retinal disease in small rodents, providing a valuable tool for the imaging of the rodent retina over time. FA is a semi-invasive technique that requires the systemic injection of the dye fluorescein. Approximately 80% of fluorescein is bound to blood proteins while the remaining fluorescein circulates in the bloodstream and fluoresces when excited by blue light. FA provides two-dimensional images or retinal vasculature while it has limited access to the deep retinal capillary plexus and the choroidal vasculature. OCTA on the other hand, is a less invasive technique that does not require dye injection and produces high-resolution three-dimensional images of the retinal and choroidal vasculature. OCTA detects changes in the OCT reflectance signal resulting from the flow of red blood cells (RBCs). This can lead to artifacts related to RBCs flow and to motion artifacts due to eye movements. Despite these limitations, OCTA is increasingly used in the clinics and could potentially provide more information on eye pathophysiology combined with other imaging techniques.

Another recently established imaging tool is the MC imaging of the fundus, recently developed by Heidelberg engineering (Heidelberg Engineering GmbH, Heidelberg, Germany). MC imaging uses three different wavelengths, blue (486 nm), green (518 nm) and infrared (815 nm), to provide information about the superficial retina, the vascular details of the retina and retinal pigment epithelium (RPE) and choroidal structures, respectively, providing a pseudocolor image of the retina. While MC imaging has gained interest among ophthalmologists, it has not yet been evaluated as a monitoring tool for murine CNV.

The aim of the present study is to evaluate the correlation of CNV lesion measurements between the semi or non-invasive imaging techniques FA, MC imaging and OCTA, with histological preparations of choroidal-RPE whole mounts.

**MATERIALS AND METHODS**

**Ethical Approval** All animals were treated according to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and after government approval according to the Federal Swiss Regulation on Animal Welfare.

**Animals** B6.N.Cg-Tg(Csf1r-EGFP)1Hume/J (MacGreen) heterozygous adult mice were used. The mice were maintained at the Department of Clinical Research, University Hospital of Bern, under conditions that are described elsewhere.

**Anesthesia** For anesthesia, necessary for CNV induction and in vivo imaging, the mice were injected subcutaneously with medetomidine (1 mg/kg Dormitor 1 mg/mL; Provet AG, Lyssach, Switzerland) and ketamine (80 mg/kg Ketalar 50 mg/mL; Parke-Davis, Zurich, Switzerland). For anesthesia reversal, atipamezole (2.25 mg/kg Antisedan 5 mg/mL; Provet AG), an antagonist of medetomidine, was administrated at the earliest 30 min after anesthesia.

**Choroidal Neovascularization Induction** Experimental CNV was induced using laser photocoagulation. A 532-nm argon laser (Visulas 532s; Carl Zeiss Meditec AG, Oberkochen, Germany) with a slit-lamp adapter (Iridex Corporation, Mountain View, CA, USA) on a slit-lamp (BM900; Haag-Streit AG, Koeniz, Switzerland) was used for the CNV induction. Pupil dilation was achieved with application of tropicamide 0.5% phenylephrine 2.5% eyedrops (Hospital Pharmacy, Inselspital, Bern, Switzerland). Three laser lesions (100 ms, 300 mW, 50 µm size) were applied around the optic nerve head of each eye.

**Optical Coherence Tomography Angiography** OCTA was performed on a Zeiss PLEX Elite 9000 device (Carl Zeiss Meditec AG, Jena, Germany) after pupil dilation with tropicamide 0.5% phenylephrine 2.5% eyedrops. A 28 D lens (Volk Optical Inc., OH, USA) in front of PLEX Elite 9000 device with 3×3 mm² scanning dimension (scaled for humans) was used. The different en face OCTA images obtained included the outer retina to choriocapillaris image (ORCC), the choriocapillaris image (CC), the RPE-RPE fit image and the retina image. The images were exported as BMP files with a resolution of 1024×1024 pixels for CNV area measurements.

**Multicolor Imaging** Immediately after OCTA, mice were imaged using the Multicolor module of a Heidelberg Spectralis HRA 2 system (Heidelberg Engineering GmbH, Heidelberg, Germany) with a widefield 55° lens (Heidelberg Engineering GmbH, Heidelberg, Germany). Images of 768×768 pixels were acquired and exported as tagged image file format (TIF) files.

**Fluorescein Angiography** FA was performed after MC and immediately after the subcutaneous injection of 50 µL fluorescein (0.01%; Faure; Novartis, Switzerland), diluted in 1× phosphate buffered saline (PBS). Images were acquired using the Spectralis HRA 2 system with an ultra-widefield 102° lens (Heidelberg Engineering GmbH, Heidelberg, Germany). Early phase images were acquired during the first 90 s of fluorescein injection, while late phase images were acquired approximately 10 min later. All images were acquired in a resolution of 1536×1536 pixels and were exported as TIF files.

**Choroidal-Retinal Pigment Epithelium Whole Mounts** After imaging, the mice were euthanized with CO₂ inhalation and their eyes were removed and fixed in 4% paraformaldehyde solution (PFA; pH 7.4) for 10 min at room temperature. The cornea, lens and retina were removed and the choroid-RPE complex was incubated for 50 min in 4% PFA (pH 7.4), followed by washing in 1×PBS, 0.5% TritonX-100 (Sigma-Aldrich, St. Louis, MO, USA). Tissues were incubated with isolectin GS-IB4 from Griffonia simplicifolia (Alexa Fluor 647
conjugate; 1:100; Thermo Fisher Scientific, Waltham, MA, USA) at 4°C overnight under continuous shaking. The samples were washed in 1×PBS, four radial cuts were made and the tissues were mounted on a slide with the RPE facing up.

**Microscopy** Microscopy was performed on equipment provided by the Microscopy Imaging Center (MIC), University of Bern, Switzerland. An inverted Zeiss LSM 710 fluorescence confocal microscope (Carl Zeiss Meditec AG, Jena, Germany) was used for the examination of choroidal-RPE whole mounts. Tile scans (3×3) z-stacks of 100-110 μm with 5 μm intervals were obtained capturing the CNV lesions with the optic nerve positioned at the center of the image. Maximum intensity projections were created in ZEN 2.5 software (Carl Zeiss Meditec AG, Jena, Germany) and exported as TIF files.

**Quantification of the Choroidal Neovascularization Areas**

Image J (version 1.51; http://imagej.nih.gov by the National Institutes of Health, Bethesda, MD, USA) was used for the CNV area measurements. In images obtained from MC, FA, and OCTA CNV areas were measured in pixel since the scale bars provided by the Spectralis and the PLEX Elite system are calculated for human eyes and are not accurate in mice\[17\]. For choroidal-RPE whole mounts, CNV areas were measured in both pixels and mm². Unedited images were opened in Image J and the CNV area was delineated and measured using the polygon selection tool function.

**Statistical Analysis** Prism 8 (Softpad Software, Inc., La Jolla, CA, USA) and IBM SPSS Statistics 25 software (SPSS Inc., Chicago, IL) were used for the statistical analysis. CNV areas were measured by two different observers in all different modalities used. To evaluate the correlation of different observers’ ratings, intraclass correlation coefficient (ICC) type 2 (2-way random model) and its 95% confidence intervals (CI) were calculated. To compare different imaging methods with histology the mean pixel values of the two observers were used. Spearman’s rank correlation coefficient (Spearman’s r) was calculated for the comparison between FA, MC and OCTA data and data derived from histology. P<0.05 were considered statistically significant.

**RESULTS**

**Imaging of the Choroidal Neovascularization Area with Different Modalities** Individual laser spots were compared using different imaging modalities (Figure 1). In choroidal-RPE whole mounts the CNV areas could be identified as isolectin GS-IB4 positive signal under the confocal microscope (Figure 1A and 1F). In MC imaging, the pseudocolor image, derived from the combination of blue, green and infrared reflectance, was used for the measurement of CNV areas (Figure 1B and 1G). For FA, an early (Figure 1C, 1H) and a late phase image (Figure 1D and 1I) was obtained per eye. Fluorescein leakage was observed in both early and late phase, while it was more pronounced in the late phase. In OCTA, CNV areas were measured in the RPE-RPE fit image (Figure 1E and 1J) based on previous studies\[18\]. In all imaging modalities, CNV areas were delineated manually by two independent observers, as shown in Figure 1, and were measured with the image J software.

**Images Acquired with Optical Coherence Tomography Angiography and Multicolor Fundus Imaging** Four OCTA en face images were exported, generated from four different slabs. The outer retina to choriocapillaris (ORCC) image (Figure 2A), the choriocapillaris (CC) image (Figure 2B), the RPE-RPE fit image (Figure 2C) and the retina image (Figure 2D). The area of CNV lesions appeared hyporeflective in the ORCC image. In CC and RPE-RPE fit images CNV areas were detected as hyperreflective, while in the retina image neovascularization was barely detectable. A dark ring surrounding the CNV area was seen in the RPE-RPE fit images (Figure 2C) and the CNV areas were measured inside this ring. In MC images, blue and green reflectance images, corresponding to the inner retina and vitreoretinal interface, and retinal vascular details in humans, appeared identical (Figure 2E and 2F). In the infrared image, corresponding to RPE and choroidal structures, CNV areas were clearly seen and were surrounded by a hyperreflective ring (Figure 2G). The pseudocolor image obtained from the combination of blue, green and infrared reflectance images was used for the analysis and the CNV area was measured as the area inside the hyperreflective ring (Figure 2H).

**Interobserver Agreement** The interobserver reliability was assessed by calculating the ICC and CI and by constructing Bland-Altman plots. The interobserver reliability was excellent for FA early (ICC=0.976) and FA late (ICC=0.964), good for whole mounts (ICC=0.896) and MC imaging (ICC=0.846) and moderate for OCTA (ICC=0.603; Figure 3A-3E and Table 1). Bland-Altman plots for whole mounts, FA early and OCTA are depicted in Figure 3F-3H and the values obtained from the analysis are shown in Table 2.

**Correlation Between Different Imaging Modalities and Whole Mount Preparations** The agreement between the measurements obtained by different imaging modalities and choroidal-RPE whole mounts was evaluated by calculation of Spearman’s correlation (Table 3) and construction of Bland-Altman plots (Figure 4A-4D; Table 4). Mean CNV area measured on the whole mounts was better correlated with areas measured in the FA early (Spearman’s r=0.7642), while FA late and MC showed a moderate correlation (Spearman’s r=0.7097 and 0.7418, respectively) with whole mounts. OCTA correlated poorly with whole mount measurements, having a Spearman’s r of 0.05716 (Table 3). Bland-Altman plots of the best (FA early) and the worst (OCTA) correlated modalities are presented in Figure 4E, 4F. For better comparison of the data
obtained by different modalities, pixel measurements of CNV area in whole mounts were used for the construction of Bland-Altman plots.

**DISCUSSION**

In experimental ophthalmology, histology remains the gold standard for investigation of retinal pathology. However, the
many disadvantages associated with histology have led to the utilization of imaging techniques that can provide information about retinal pathophysiology in vivo and in a longitudinal manner. In the present study, we evaluated the agreement of different in vivo imaging modalities, namely FA, MC imaging and OCTA, with histological preparations, to measure CNV areas in a murine laser-induced CNV model. The presented data generally revealed high interobserver agreement in the measurements obtained by different modalities. However, when different in vivo imaging modalities were compared to measurements on choroidal-RPE whole mounts, FA and MC showed a good agreement while OCTA was poorly correlated with whole mount measurements. To date, FA along with indocyanine green angiography (ICGA) and spectral domain optical coherence tomography, represent the standard tools for the detection of vascular abnormalities in human retina and choroid. FA is an semi-invasive technique, since it requires systemic injection of the dye fluorescein, and despite its ability to focus in the superficial retinal vasculature, it has limited access to the visualization of...
Table 1 Calculation of ICC between different observers

<table>
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<tr>
<th>Parameters</th>
<th>Bias</th>
<th>SD of Bias</th>
<th>Lower LoA</th>
<th>Upper LoA</th>
<th>Significance</th>
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<tr>
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<tr>
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<tr>
<td>OCTA</td>
<td>808.1</td>
<td>554.9</td>
<td>-279.6</td>
<td>1896</td>
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</tr>
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</table>

Bias: Mean difference between two observers; SD: Standard deviation; LoA: Limits of agreement; FA: Fluorescein angiography; MC: Multicolor fundus imaging; OCTA: Optical coherence tomography angiography.

Table 2 Statistics obtained from Bland-Altman analysis of different methods

<table>
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<tr>
<th>Parameters</th>
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<th>Lower LoA</th>
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<tr>
<td>Whole mounts</td>
<td>0.7642</td>
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<td>P&lt;0.0001</td>
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<td>FA early</td>
<td>0.7097</td>
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<td>0.5011-0.8759</td>
<td>P&lt;0.0001</td>
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<td>FA late</td>
<td>0.4138</td>
<td>0.3011-0.8759</td>
<td>0.05716</td>
<td>-0.3956-0.4876</td>
<td>P=0.05</td>
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<tr>
<td>OCTA</td>
<td>0.05716</td>
<td>-0.3956-0.4876</td>
<td>0.05716</td>
<td>-0.3956-0.4876</td>
<td>P=0.05</td>
</tr>
</tbody>
</table>

Spearman’s $r$ was calculated to compare the agreement of CNV area measurements in the in vivo imaging modalities with measurements in choroidal-RPE whole mounts. FA: Fluorescein angiography; MC: Multicolor fundus imaging; OCTA: Optical coherence tomography angiography.

Table 3 Statistics obtained from Bland-Altman analysis of different methods

<table>
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<th>Parameters</th>
<th>Bias</th>
<th>SD of bias</th>
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<tbody>
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<td>Whole mounts</td>
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<td>12299</td>
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Comparison of CNV area measurements in in vivo imaging modalities and choroidal-RPE whole mounts. SD: Standard deviation; LoA: Limits of agreement; FA: Fluorescein angiography; MC: Multicolor fundus imaging; OCTA: Optical coherence tomography angiography.

Table 4 Statistics obtained from Bland-Altman analysis of different methods

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<th>Lower LoA</th>
<th>Upper LoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole mounts</td>
<td>0.976</td>
<td>0.949-0.989</td>
<td>0.964</td>
<td>0.925-0.983</td>
</tr>
<tr>
<td>FA early</td>
<td>0.846</td>
<td>0.698-0.924</td>
<td>0.603</td>
<td>0.253-0.814</td>
</tr>
<tr>
<td>FA late</td>
<td>0.964</td>
<td>0.925-0.983</td>
<td>0.603</td>
<td>0.253-0.814</td>
</tr>
<tr>
<td>MC</td>
<td>0.603</td>
<td>0.253-0.814</td>
<td>0.603</td>
<td>0.253-0.814</td>
</tr>
</tbody>
</table>

ICC: Intraclass correlation coefficient; Obs: Observer; 95%CI: 95% confidence interval; FA: Fluorescein angiography; MC: Multicolor fundus imaging; OCTA: Optical coherence tomography angiography.

This weakness can be overcome by the recent development of OCTA, which is a non-invasive and more efficient tool for the imaging of retinal and choroidal vasculature based on blood flow\(^{[12,24]}\). OCTA is widely used in clinical ophthalmoogy as a tool for the study of vascular pathology in many retinal diseases and it has been recently used as an imaging tool of retinal vasculature in naïve mice and mice subjected to laser-induced CNV, using an RTVue XR Avanti system (Optovue, Inc., Fremont, California)\(^{[25]}\). However, previous studies have shown a lack of sensitivity and specificity of OCTA compared to FA imaging modality to detect CNV, while such comparisons with histological preparations is missing.

Since OCTA requires repeated scans of the same location in the eye in order to detect blood flow, eye movements can increase noise and lead to motion artifacts and overestimation of the blood flow signal. Moreover, projections artifacts from vessels in the superficial retina that can be seen in the deeper retina and vice versa can prevent the recognition of CNV or can inaccurately recognize the presence of CNV\(^{[26-27]}\). As shown in Figure 2A, the location of CNV lesions appeared hyporeflective in the ORCC images, most probably due to this kind of projection artifacts. The above mentioned limitations of OCTA along with the poor correlation of our CNV measurements in OCTA with CNV measurements in histological preparations, indicate that the Zeiss PLEX Elite 9000 OCTA system cannot be used as a reliable method for CNV measurements in mice.

Another imaging modality extensively used in the clinical practice is the MC imaging system. MC uses lasers of different colors at the same time to capture information from different retinal structures creating a high-contrast pseudocolor image of the retina. A recent study by Muftuoglu et al\(^{[28]}\) reported differences in MC imaging compared to color fundus photography in patients with choroidal and/or retinal lesions. While the same information could be obtained by the two methods, MC imaging underestimated the size of choroidal lesions by 33%\(^{[28]}\). In our study, imaging modalities designed for humans were used for the measurement of CNV areas in mice. Thus, we were unable to use the scale bars provided by the different imaging modalities for the precise estimation of CNV size. CNV areas were clearly seen in the infrared image of the retina. A recent study by Muftuoglu et al\(^{[29-30]}\).

To summarize, the present study shows that FA and MC imaging, but not OCTA performed on the Zeiss PLEX Elite 9000 device, correlate well with histological CNV measurements in isolectin GS-IB4-stained choroidal-RPE.
whole mounts and therefore FA and MC may be better suited for longitudinal monitoring of CNV lesions in mice. However, caution must be taken when utilizing imaging modalities designed for humans in small rodents. Most importantly, since the mouse eye dimensions and curvature greatly differ from human eyes and the scale bars in the imaging modalities used in the present study are not accurate in small rodents, measurements and comparisons of the CNV areas were done in pixel. Thus, the comparisons were made on the proportional size of CNV rather than the actual size.

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anti-VEGF therapy in treatment-naïve neovascular age-related macular