ABCA4-related retinopathy is the most common inherited juvenile retinal dystrophy and is caused by mutations in the ATP-binding cassette A4 (ABCA4) gene, encoding a transmembrane transporter in the outer photoreceptor segments. Defects in the ABCA4 protein lead to progressive accumulation of visual cycle end products such as lipofuscin, and eventually destruction of the retinal pigment epithelium (RPE) and photoreceptors with progressive visual loss.

Clinically, the excessive accumulation of visual cycle end products can be visualized by short-wavelength fundus autofluorescence (FAF) imaging and is characterized by an overall increased background FAF intensity and hyperautofluorescent flecks. During disease progression, these flecks typically expand in a centrifugal distribution and become more hypautofluorescent as RPE atrophy develops. Therefore, FAF is a useful technique to monitor disease progression in ABCA4-related retinopathy.

The classically applied short-wavelength FAF uses blue excitation light (488 nm), and FAF emission detection between 500 and 700 nm. However, individual fluorophores feature distinct excitation as well as emission spectra. Emerging therapeutic approaches require monitoring options for subtle retinal changes and treatment effects, ideally over a relatively short period. Spectrally resolved FAF may therefore be aspired to, as it might give more differentiated insights into the composition and spreading of morphologic disease alterations. A novel confocal FAF device (EIDON; CenterVue, Padova, Italy) has recently been developed and introduced. It allows for separation of short and long FAF emission wavelengths (“color-FAF imaging”).

Our study aimed to describe the distribution of FAF emission in a short- and a long-wavelength emission spectra, using the EIDON fundus camera, and to evaluate the potential clinical use of emission channel separation in ABCA4-related retinopathy.

METHODS
This monocentric, cross-sectional case series was performed at the Department of Ophthalmology of the University of Bonn,
Germany. The study was in adherence to the Declaration of Helsinki. Institutional Review Board approval from the University of Bonn, Germany, and patients’ written informed consent were obtained after explanation of the nature and possible consequences of the study.

**Subjects**

Patients with ABCA4-related retinopathy were recruited from the local retinal dystrophy clinic. The diagnosis of ABCA4-related retinopathy was defined by the presence of at least one disease-causing mutation in ABCA4 and a consistent phenotype. If only one disease-causing mutation in ABCA4 was found, patients underwent next-generation sequencing to rule out other retinal diseases mimicking ABCA4-related retinopathy. Only patients with clear media and without ocular comorbidities affecting visual function or any additional retinal pathology or previous vitreoretinal surgery were included.

Severity of phenotypic presentation of the retina with flecks and atrophy was classified according to the Fishman classification for fundus flavimaculatus. Group 1 eyes showed pigmentary changes restricted to the fovea, often accompanied by a ring of flecks within one disc diameter around the fovea. Group 2 eyes revealed flecks beyond the vascular arcades, often also nasal to the optic disc. A partial resorption of the pigmentary changes restricted to the fovea, often accompanied by a ring of flecks within one disc diameter around the fovea. Finally, group 4 eyes demonstrated extensive choriocapillaris and retinal pigment epithelial cell atrophy throughout the fundus.

**Clinical Examination and Imaging**

All patients underwent a complete dilated ophthalmic examination and multimodal imaging. The imaging protocol consisted of spectral-domain optical coherence tomography (OCT; Spectralis HRA+OCT, Heidelberg Engineering, Heidelberg, Germany), as well as confocal color fundus photos (cCFPs), infrared (IR) imaging, and color fundus autofluorescence (color-FAF) using the EIDON fundus camera. The EIDON fundus camera is a fully automated retinal imaging device using autoalignment, autofocus (range, −12 to +15 diopters), autoexposure, and autocapture of the images (Sarao V, et al. IOVS 2018;59:ARVO E-Abstract 4653). It enables recording of confocal light-emitting diode (LED) true color fundus photos (cCFP, 440–650 nm), IR reflectance (825–870 nm) images, and color-FAF images with blue excitation light (440–475 nm, peak at 450 nm). For signal detection, a barrier filter with cutoff at 500 nm is used. Color-FAF emission was simultaneously measured within a short-wavelength range between 500 and 560 nm (green emission fluorescent component, GEFC), and within a long-wavelength range between 560 and 700 nm (red emission fluorescent component, REFC) using a line-scanning principle; thereby, the sensor raster scans the posterior pole for illumination and imaging, using a rotating mirror. FAF images can be illustrated in gray values (as conventional FAF intensity images) or color coded (as color-FAF images).

EIDON images cover the central 60° (horizontal) × 55° (vertical) of the posterior pole in a single exposure, using an internal central fixation target. The sensor resolution equals 14 megapixels (4608 × 3288), corresponding to an image resolution of 60 pixels per degree. The retinal resolution equals 15 μm. Radiant exposure for white and blue LED lies well below the standard limits defined by ISO 15004-2 (regulatory standard for light hazard protection) and falls into the category “ophthalmic instruments for which no potential light hazard exists.” The entire imaging procedure with EIDON is illustrated in Figure 1.

**Data Analysis**

Data were collected and processed by using commercially available Microsoft Excel 2010 (Redmond, WA, USA). Values are presented as mean ± standard deviation (SD). Color-FAF images were transferred to Image J (https://imagej.nih.gov/ij/; provided in the public domain by the National Institutes of Health, Bethesda, MD, USA) in order to separate the GEFC and the REFC by using the “split channels” function. No further image processing was needed. Corresponding morphologic structures were compared between the different imaging modalities. The distribution of GEFC and REFC flecks was analyzed and quantified by using an extended ETDRS grid with ring diameters of 1 mm (center), 3 mm (inner ring), 6 mm (outer ring), and 9 mm (supplementary ring). Finally, color-FAF images were imported in the custom-made analysis software “FAF Color Segmentation Tool” developed by CenterVue that allows for display of fluorescence intensity and emission wavelengths (GEFC to REFC) as a two-dimensional graph (see Fig. 6). Hence, each pixel of the image is represented in an xy-graph with the proportion of GEFC to REFC on the x-axis, and the FAF intensity on the y-axis. Thereby, characteristic distribution clouds could be identified, and specific regions of interest could be marked and highlighted within the image.
RESULTS

Cohort Characteristics

A total of 80 eyes of 40 patients (50% female) with ABCA4-related retinopathy were included in the study. Mean age was 43.6 ± 18 years (range, 11–81 years). Biallelic ABCA4 mutations were found in 37 of 40 patients. According to the morphologic classification, 34 eyes were assigned to group 1; 32 eyes to group 2; 10 eyes to group 3; and 4 eyes to group 4. Of note, both eyes of each patient always met the same subgroup criteria. A total of six eyes (7.5%) were pseudophakic. Demographic and functional data of each subgroup are summarized in the Table.

Distribution of Flecks

In cCFP images, disease-characteristic flecks were clearly visible, accentuated at the posterior pole with or without distribution beyond the vascular arcades according to the phenotypic presentation as reflected in the subgroup classification (Figs. 2, 3). In FAF, these flecks primarily presented as hyperautofluorescent, coded bright (white) in gray-scale FAF intensity images, and reddish or greenish in color-FAF images. Resorbed flecks and areas of RPE atrophy were hypoautofluorescent, visualized by dark areas in both FAF modalities (Fig. 3). The prevalence of hyperautofluorescent flecks was 64% in eyes of subgroup 1; 100% in subgroup 2; and not assessable in subgroups 3 and 4 owing to lesions outside of the 9-mm grid and/or to very advanced disease stage without identifiable individual flecks (Table).

Green and Red Emission Fluorescent Component

Hyperautofluorescent flecks in color-FAF images revealed a characteristic distribution of predominant emission wavelength. After splitting GEFC and REFC, flecks were still visible in both spectral channels. However, most flecks revealed a primary emission in either the short (green) or the long (red) wavelength (Figs. 2, 3). The prevalence of GEFC flecks within the macular 9-mm ring was 3.33 times higher than for REFC flecks for subgroup 1, and 4.67 times higher for subgroup 2. Flecks located more centrally generally featured a higher proportion of short-wavelength autofluorescence emission coded greenish in the color-FAF images. However, more peripherally located flecks more often showed long-wavelength autofluorescence emission, and appeared reddish. In subgroup 2, the ratio of REFC to GEFC was on average 3.2

<table>
<thead>
<tr>
<th></th>
<th>All Subjects</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No., n (%)</td>
<td>40 (100)</td>
<td>17 (42.5)</td>
<td>16 (40)</td>
<td>5 (12.5)</td>
<td>2 (5)</td>
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<td>Age, y</td>
<td>42.5 ± 17.9 (11–81)</td>
<td>37.5 ± 17.3 (11–62)</td>
<td>46.8 ± 19.2 (13–81)</td>
<td>45.2 ± 12.8 (36–66)</td>
<td>44.5 ± 27.6 (25–64)</td>
</tr>
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<td>Sex, female/male</td>
<td>20/20</td>
<td>9/8</td>
<td>9/7</td>
<td>1/4</td>
<td>1/1</td>
</tr>
<tr>
<td>BCVA, logMAR</td>
<td>0.72 ± 0.51 (0.0–1.7)</td>
<td>0.61 ± 0.46 (0.0–1.5)</td>
<td>0.68 ± 0.48 (0.0–1.6)</td>
<td>0.88 ± 0.58 (0.0–1.5)</td>
<td>1.48 ± 0.26 (1.2–1.7)</td>
</tr>
<tr>
<td>GEFC flecks, mean (range)</td>
<td>5.51 (0–16)</td>
<td>22.5 (8–44)</td>
<td>Not definable</td>
<td>Not definable</td>
<td>Not definable</td>
</tr>
<tr>
<td>REFC flecks, mean (range)</td>
<td>1.15 (0–4)</td>
<td>3.74 (0–14)</td>
<td>Not definable</td>
<td>Not definable</td>
<td>Not definable</td>
</tr>
</tbody>
</table>

BCVA, best corrected visual acuity.
* Values represent mean ± SD (range).
times higher in the supplementary ring (9 mm) than in the outer ETDRS ring (6 mm).

A subgroup of flecks was identified bifidly with a centrifugal sequence of predominant green to red autofluorescent components within the individual fleck, that is, the main green proportion with shorter emission wavelength was located in the central part of the fleck, whereas the main red proportion was found more peripherally (Fig. 4).

Hyperautofluorescent fundus flecks spatially correlated to subretinal deposits in OCT (Fig. 5). REFC-predominant flecks were correlated with hyperreflective deposits that disrupt external retinal layers up to the ellipsoid zone (EZ) band and displace the preserved external limiting membrane (ELM) anteriorly. In contrast, subretinal deposits associated with GEFC-predominant flecks seem to break through the ELM too. Both types of flecks showed a marked focal reduction of the outer nuclear layer thickness above the subretinal deposits (Fig. 5).

Green and Red Emission Fluorescent Component Versus FAF Intensity

Plotting of the emission spectra (GEFC to REFC) versus the intensity of an individual color-FAF image resulted in a two-dimensional graph including every data point (Fig. 6); thereby, individual structures and anatomic regions featured specific distribution characteristics. The retina represented the center of the curve. On top, with increased FAF intensity, the flecks were identified. This peak could further be divided into spectrally resolved FAF proportion and resulted in identification of the GEFC and REFC flecks. GEFC and REFC flecks showed similar FAF peak intensities but can be differentiated by their emission wavelength. Additionally, the center of many flecks displayed increased GEFC, whereas the margin of the flecks featured increased REFC. On the bottom of the plot, structures with low FAF intensity like retinal vessels, the optic nerve head, and atrophic lesions were identifiable. Retinal vessels were found to feature predominantly REFC, whereas the optic nerve head and RPE atrophy mainly showed GEFC. In the transition zone between the retina and structures of low FAF intensity, margins of RPE atrophy and rims of retinal vessels were delineated.

DISCUSSION

To our knowledge, this is the first report investigating FAF intensities of flecks secondary to ABCA4-related retinopathy on a spectrally resolved FAF imaging tool. The EIDON device allows for fully automated acquisition of three different imaging modalities (cCFP, IR, and FAF) in a large field of view within a short period of time, thus, facilitating the multimodal approach and analysis of retinal pathologies. Furthermore, the device contains two separate FAF emission detectors that

![Figure 3](image-url) Spectrally resolved fundus autofluorescence in different disease stages. Representative examples for ABCA4-related retinopathies classified in four groups with Fishman stages 1 to 4. cCFP: EIDON confocal color fundus photos; color-FAF: color-coded fundus autofluorescence intensity image with enlarged region of interest. Flecks with predominant green and red emission fluorescent component are highlighted with respective arrows.

![Figure 4](image-url) Green and red fundus autofluorescence emission components in flecks with pisiform growths. ABCA4-related flecks with pisiform growth featured increased GEFC located toward the macular center and increased REFC toward the retinal periphery. cCFP: EIDON confocal color fundus photography; GEFC: 500–560 nm; REFC: 560–700 nm; color-FAF: color-coded fundus autofluorescence intensity image. Green and red arrows mark flecks with increased GEFC and REFC, respectively. Arrowheads indicate pisiform flecks with both GEFC and REFC, and allow comprehensive reconstruction of centrifugal growth of the flecks.
amine (A2E). However, there are many other autofluorescent noids of RPE lipofuscin as visual cycle by-products. One of the major fluorophores in the photoreceptor outer segments is thought to be the bis-retinoid N-retinyl-N-retinylidene ethanolamine (A2E). However, there are many other autofluorescent bisretinoids including A2E photoisomers. According to a recent FAF study on Stargardt disease investigating short-wavelength and near-infrared autofluorescence, bisretinoids in the outer segments of degenerating photoreceptors might also contribute to alterations in FAF signal, in particular after disruption of the photoreceptor cells. Cukras and coworkers have assigned variations in FAF intensity in single flecks to intracellular events such as changes of the lipofuscin and melanin content in RPE cells. This hypothesis was confirmed by evaluation of flecks in short-wavelength FAF; this known to predominantly derive from bisretinoid components in lipofuscin, and in near-infrared FAF, thought to originate from the melanin compartment in the RPE and the choroid. Therefore, changes in the composition of the deposits and/or the surrounding environment might influence the proportion of FAF intensity detected in the two wavelength ranges in this study. Remodeling of the molecular composition in flecks might be one of the most subtle retinal changes in disease progression, implicating spectrally resolved FAF as a possible surrogate marker to be used in future interventional trials.

Both anatomic and functional clinical endpoints for evaluation of treatment effects in ABCA4-related retinopathy represent a challenge, as the point-of-no-return for irreversible structural and functional retinal damage is still unknown. Furthermore, longitudinal data are missing, also with regard to other imaging tools, such as quantitative autofluorescence (qAF), that visualize earliest pathognomonic retinal alterations. Future studies including prospective investigations should therefore be aspired to in order to gain further insights into the natural history and underlying mechanisms of ABCA4-related retinopathy.

Using FAF, a further assessment of the metabolic environment in ABCA4-related retinopathy besides excitation and emission spectra can be achieved by fluorescence lifetime imaging ophthalmoscopy (FLIO), which has been shown to be unique for individual fluorophores, and to reveal distinct longitudinal changes in disease progression. Thereby, peripherally located flecks initially present with short fluorescence lifetimes, whereas more central flecks exhibit longer fluorescence lifetimes, indicating differences in the composition of these deposits and their remodeling over time.

By graphic representation of the FAF intensity versus the FAF emission spectrum (Fig. 6), specific landmarks of the retina such as the optic nerve head and retinal vessels, as well as disease-specific features, could be discriminated. Thereby, specific regions of interest such as flecks and margins of atrophy can further be separated, individually depicted and analyzed, with the potential to facilitate future approaches of data quantification. Apart from ABCA4-related retinopathy, this tool might be of interest also for various other retinal diseases including age-related macular degeneration. In this context, the solely available studies using the EIDON fundus camera are described. The latter have shown that GEFC corresponds to residual debris or drusenoid material in areas of geographic atrophy, and that images correlate well to conventional FAF images acquired with 488-nm excitation wavelength.

Interestingly, we observed that also structures without underlying RPE and with commonly known low or absent FAF intensity, such as atrophic areas, retinal scars, and the optic nerve head, were detected and predominantly featured GEFC.
In contrast, low FAF intensity in the area of the vessels appeared predominantly with REFC. The origin of the detected fluorescence signal has not been yet entirely clarified. Similar findings with measured autofluorescence signal in the optic nerve head, vessels, and atrophic areas have also been found when using FLIO.32,33 A possible explanation is increased autofluorescence emission after excitation with 450 nm (or 473 nm as used in FLIO), as green-emitting fluorophores are more efficiently stimulated at shorter wavelengths than at 488 nm, which is commonly used for FAF intensity imaging.16 As the emission filter has a sharp cutoff at 500 nm, filter leakage is unlikely to contribute to this phenomenon. Also, the fraction of internally reflected and scattered light is very small.

The limitations of this study included the cross-sectional design, which did not allow conclusions on the longitudinal evolution of the FAF emission pattern of flecks secondary to ABCA4-related retinopathy. We are currently conducting longitudinal observations. Furthermore, the settings of the novel device are predefined and cannot be changed to date. Modification of the excitation spectra, as well as the limits of the emission detection, might allow further information in addressing different fluorophores. Also, signal in areas of low fluorescence intensity was detected with variable intensity, as the device uses an automated intensity scaling algorithm without internal reference, in contrast to qAF imaging. Therefore, areas of low FAF can be detected with variable intensity depending on the degree of the strongest FAF.
EIDON in ABCA4-Related Retinopathy


