Inflammatory and Neuronal Biomarkers Associated With Retinal Thinning in Pediatric HIV

Charlotte Blokhuis,1 Susanne Doeleman,1 Sophie Cohen,1 Nazi Demirkaya,2 Henriëtte J. Scherpier,1 Neeljte A. Kootstra,3 Jens Kuhle,4 Charlotte E. Teunissen,5 Frank D. Verbraak,2,6,7 and Dasja Pajkrt1

1Department of Hematology, Immunology and Infectious Diseases, Emma Children’s Hospital/Academic Medical Center, University of Amsterdam, The Netherlands
2Department of Ophthalmology, Academic Medical Center, University of Amsterdam, The Netherlands
3Department of Experimental Immunology, Academic Medical Center, Amsterdam, The Netherlands
4Neurology, Departments of Medicine, Biomedicine and Clinical Research, University Hospital Basel, Basel, Switzerland
5Neurochemistry Laboratory and Biobank, Department of Clinical Chemistry, VU University Medical Center and Neurocampus Amsterdam, The Netherlands
6Department of Biomedical Engineering and Physics, Academic Medical Center, University of Amsterdam, The Netherlands
7Department of Ophthalmology, VU University Medical Center, Amsterdam, The Netherlands

Correspondence: Charlotte Blokhuis, Department of Pediatric Hematology, Immunology, and Infectious Diseases, Emma Children’s Hospital/Academic Medical Center, Meibergdreef 9, 1105AZ Amsterdam, The Netherlands; c.blokhuis@amc.nl.

CB and SD contributed equally to the work presented here and should therefore be regarded as equivalent authors.

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PURPOSE. The pathophysiology of neuroretinal thinning in children with human immunodeficiency virus (HIV) is poorly understood. The current study aimed to assess whether neuroretinal thinning in clinically stable perinatally HIV-infected children was associated with biomarkers of immune activation, inflammation, and neuronal damage.

METHODS. Inflammation-associated and neuronal damage markers were measured in blood and cerebrospinal fluid (CSF) of HIV-infected children aged 8 to 18 years. Using mixed-effects regression analyses, we assessed associations between these biomarkers and neuroretinal layer thickness, as measured with spectral-domain optical coherence tomography.

RESULTS. Thirty-two HIV-infected children (median age 13.6 years, 50% male) were included. Blood plasma levels of interleukin-6, monocyte chemoattractant protein-1, and soluble intercellular adhesion molecule-1 were inversely correlated with foveal inner plexiform layer thickness (coef = −4.40, P < 0.001; coef = −9.67, P = 0.047; coef = −10.48, P = 0.042, respectively). Plasma interleukin-6 was inversely correlated with foveal ganglion cell layer thickness (coef = −2.49, P = 0.010). Total Tau levels in CSF were inversely correlated with outer nuclear layer and inner segments thickness (foveal: coef = −19.5, P = 0.029; pericentral: coef = −18.09, P = 0.006) and pericentral total retinal thickness (coef = −28.2, P = 0.017).

CONCLUSIONS. Neuroretinal thinning was associated with inflammation-associated and neuronal injury biomarkers in a cohort of antiretroviral therapy-treated perinatally HIV-infected children. These findings suggest that ongoing immune activation, inflammation, and neuronal injury occur in parallel with retinal thinning in pediatric HIV.

Keywords: perinatally HIV-infected children, retina, SD-OCT, neuronal injury, immune activation, inflammation

Human immunodeficiency virus (HIV) infection has been associated with retinal structural abnormalities and subtle visual impairments in perinatally infected children, despite adequate viral suppression and absence of ocular opportunistic infections (Fig.1–5 As the retina contains neuronal tissue, the pathogenesis of retinal structural damage in HIV infection may have similarities with central nervous system (CNS) damage in HIV. This hypothesis is supported by the previously detected association between retinal thinning and white matter microstructural injury in HIV patients.5 The pathogenesis of retinal and cerebral abnormalities in pediatric HIV is poorly understood, and may not only involve direct injury by HIV and/or antiretroviral therapy (cART), but also chronic immune activation, inflammation, and microvascularopathy.5,6 Several biomarkers associated with systemic inflammation are increased in plasma of HIV-infected children, including C-reactive protein (CRP), monocyte chemoattractant protein (MCP-1), soluble CD14 (sCD14), soluble intercellular cell adhesion molecule-1 (sICAM-1), and soluble vascular cell adhesion molecule-1 (sVCAM-1).7–11 Studies in HIV-infected adults report that immune activation and inflammation correlate with biochemical and neuroimaging markers of neuronal injury, including elevated cerebrospinal fluid (CSF) levels of neurofilament light chain (NFL), poorer white matter microstructural integrity, and altered magnetic resonance spectroscopy neurometabolites.12–14 Further, inflammation-associated markers MCP-1 and interleukin (IL)-6 in plasma have previously been shown to impair blood-retinal barrier (BRB) function, leading to increased vulnerability of the retina to potential insults by HIV and/or inflammation.15
Increased levels of neuronal cytoskeleton components, such as neurofilaments and Tau protein, have been associated with HIV-associated neurocognitive disorders (HANDs) in adults.\textsuperscript{16,17} Release and aggregation of these proteins have also been linked to several forms of non-HIV-associated retinal pathology,\textsuperscript{18,19} prompting us to study these markers in the context of HIV-related retinal thinning.

The current study aimed to assess whether increased immune activation, inflammation, and neuronal injury is associated with retinal thinning in clinically stable perinatally HIV-infected children. To investigate this, we looked for potential correlations between spectral-domain optical coherence tomography (SD-OCT)-measured retinal thickness (RT), and systemic and intrathecal biomarkers of immune activation, inflammation, and neuronal injury in a cohort of perinatally HIV-infected children, of whom most were on long-time suppressive cART.

**METHODS**

This study is part of the NOVICE study, an interdisciplinary observational cross-sectional case-control study; assessing neurological, cognitive, and ophthalmic performance in perinatally HIV-infected children as compared to uninfected controls matched for age, sex, ethnicity, and socioeconomic status (SES) in The Netherlands (Dutch Trial Registry ID NTR4074).\textsuperscript{20} This study adhered to the tenets of the Declaration of Helsinki and informed consent was obtained from all parents and from children aged 12 and older. The research was approved by the investigational review board at the Academic Medical Center in Amsterdam.

**Study Participants**

We included participants from the NOVICE cohort, consisting of perinatally HIV-1-infected children between 8 and 18 years old, recruited from the Amsterdam Medical Center in Amsterdam between December 2012 and January 2014.\textsuperscript{20} Exclusion criteria for participation in this study were traumatic brain injury, (history of) intracerebral neoplasms, chronic HIV-unrelated neurological disease, psychological disorders, and absence of biomarker data. Additional ophthalmic exclusion criteria were visual acuity below 0.1 on the logMAR chart, intraocular pressure above 21 mm Hg, high refractive errors (spherical equivalent [SE] exceeding >+5.5 or <-8.5 D), significant media opacities, and a history of ocular surgery or disease.\textsuperscript{3}

Of the 36 HIV-infected children included in this cohort, we selected those with paired OCT and laboratory data available. This led to exclusion of three children for whom OCT data were unavailable (no consent, \(n=2\); history of bilateral cytomegalovirus retinitis, \(n=1\)). We additionally excluded OCT data of eyes affected with retinal abnormalities (uveitis, \(n=1\); congenital toxoplasmosis lesions, \(n=1\)); for these participants, we excluded measurements from the left (affected) eye, and used measurements from the right eye.\textsuperscript{3} Finally, we excluded one participant with missing laboratory data.

**SD-OCT and Retinal Layer Segmentation**

Thickness of individual retinal layers was assessed using SD-OCT (Topcon 3D OCT-100; Topcon, Inc., Paramus, NJ, USA) as described previously.\textsuperscript{3} In short, OCT images were obtained using 3D macular and disc volume scan protocols. Low-quality
Biomarkers of Retinal Thinning in Pediatric HIV

### Participant Characteristics

<table>
<thead>
<tr>
<th>HIV-Infected Children, N = 32</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographic characteristics</strong></td>
</tr>
<tr>
<td>Sex, male</td>
</tr>
<tr>
<td>Age at OCT, y</td>
</tr>
<tr>
<td>Ethnicity</td>
</tr>
<tr>
<td>Black</td>
</tr>
<tr>
<td>Mixed race</td>
</tr>
<tr>
<td>Other</td>
</tr>
<tr>
<td><strong>HIV- and cART-Related characteristics</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Clinical</td>
</tr>
<tr>
<td>Age at HIV diagnosis, y</td>
</tr>
<tr>
<td>CDC stage</td>
</tr>
<tr>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>HIV-encephalopathy</td>
</tr>
<tr>
<td>CD4+ T-cell counts and HIV viral load</td>
</tr>
<tr>
<td>Peak HIV viral load, log copies/mL</td>
</tr>
<tr>
<td>Nadir CD4+ T-cell count*</td>
</tr>
<tr>
<td>10^6/L</td>
</tr>
<tr>
<td>Z score</td>
</tr>
<tr>
<td>Viral suppression at study inclusion</td>
</tr>
<tr>
<td>CD4+ T-cell count at study inclusion</td>
</tr>
<tr>
<td>10^6/L</td>
</tr>
<tr>
<td>Z score</td>
</tr>
<tr>
<td>Time with CD4+ T-cell count &lt;500 10^6/L, mo</td>
</tr>
</tbody>
</table>

#### cART

| Use at inclusion | 27 (84) |
| Interrupted/nonadherence | 4 (13) |
| Naive | 1 (3) |
| Age at cART initiation, y | 2.6 (1.2 to 6.2) |
| Duration cART use, y | 10.7 (5.3 to 13.7) |

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Demographic, HIV- and cART-related characteristics of 32 included participants, displayed as median (IQR) or N (%). CDC, Centers for Disease Control and Prevention stage (N/A, no or minimal symptoms; B, moderate symptoms; C, severe symptoms or acquired immunodeficiency syndrome).

* Historical data were incomplete for peak HIV viral load (n = 28; 4 missing), nadir CD4 T-cell counts (n = 30; 2 missing), and cART initiation and duration (n = 29; 3 missing).

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Images with a Topcon image quality factor (QF) <60 were excluded. Individual neuroretinal layers were automatically segmented from 3D macular volumes using the Iowa Reference Algorithm that enables computations of individual retinal layer thickness for each of the nine macular regions as defined by the Early Treatment of Diabetic Retinopathy Study (EDTRS) (see Supplementary Fig.). For the current study, we included the total foveal and pericentral RT, as well as the thickness of retinal layers that contain neuronal tissue, most of which were affected by thinning in our cohort: the ganglion cell layer (GCL), inner plexiform layer (IPL), inner nuclear layer (INL), and outer nuclear layer + inner segments (ONL+IS).

### Biomarker Analysis

On the same day as SD-OCT, samples for biomarker analysis were collected. Blood samples were centrifuged within 2 hours at 1700g for 10 minutes, after which the supernatant was transferred into a polypropylene tube (Sarstedt, Numbrecht, Germany) and stored at –80°C until biomarker analysis.

We selected the following biomarkers representing HIV-associated immune activation, inflammation, and vascular endothelial activation that were previously found to be upregulated in our cohort and/or in other HIV-infected populations: CRP, IL-6, IL-15, interferon-gamma (IFN-γ), interferon-gamma inducible protein 10 (IP-10), MCP-1, sCD14, sICAM-1, and sVCAM-1. These inflammation-associated biomarkers were quantified in blood plasma and CSF using Meso Scale Discovery, a highly sensitive electrochemiluminescence-based immunoassay, according to the manufacturer’s instructions, except sCD14, which was analyzed using an enzyme-linked immunosorbent assay (ELISA; R&D Systems, Minneapolis, MN, USA).

Neuronal damage marker NFL was quantified in CSF using an ELISA (Uman Diagnostics, Umea, Sweden) and in serum using an in-house developed test for the Meso Scale Discovery platform, using the same antibodies as in the Uman ELISA. CSF neurofilament heavy chain (NFH) was measured using an in-house developed Luminex assay, and CSF total Tau (tTau) was measured using the Innotest (Fujirebio, Gent, Belgium).

### Statistical Analysis

Statistical analyses were performed using Stata Statistical Software, release 13 (StataCorp LP, College Station, TX, USA). We assessed associations between inflammation-associated and neuronal damage biomarkers (independent parameters) and thickness of selected retinal layers (dependent parameters) using mixed-effects multivariable linear regression. This regression model was chosen to take correlation between right and left eyes within participants into account. Biomarker levels that were reported as below or above the range of quantification were imputed using the lower or upper limit of quantification, respectively. Biomarkers were transformed using base-10 log transformation. Variables that did not approach a normal distribution were dichotomized using median splits. All analyses were adjusted for age, sex, and SE. Analyses were not corrected for OCT QF because median QF was high in both groups (median QF: HIV-infected = 85.07; controls = 85.17; P = 0.80). The threshold for statistical significance was set at a P-value of <0.05. In line with the explorative nature of this study, we did not perform power calculations or adjust for multiple comparisons, and results should be interpreted accordingly.

### Results

#### Participants

A total of 32 clinically stable HIV-infected children (50% male, median age 13.6 [interquartile range (IQR) 11.8–15.9] years) were included in the current study. Demographical and clinical characteristics of included participants are presented in Table 1. At the time of study assessment, 27 (84%) participants had been using cART for a median duration of 10.7 (IQR 5.3–13.7) years, of whom all but one (96%) were virologically suppressed. At the time of study inclusion, 27 (84%) participants had been using cART for a median duration of 10.7 (IQR 5.3–13.7) years, of whom all but one (96%) were virologically suppressed. All analyses were adjusted for age, sex, and SE.
differ from the other HIV-infected participants in terms of
demographical and clinical characteristics.

**Associations Between Biomarkers and RT**

Associations between inflammation-associated biomarkers and
RT are displayed in Table 2. Blood plasma levels of IL-6, MCP-1,
and sICAM1 inversely correlated with foveal IPL thickness (IL-
6: $\text{coef} = -4.40, P < 0.001$; MCP-1: $\text{coef} = -9.67, P = 0.047$;
sICAM1: $\text{coef} = -10.48, P = 0.042$). Further, blood plasma IL-6
levels inversely correlated with foveal GCL thickness ($\text{coef} = -2.49, P = 0.010$). CSF levels of these biomarkers were not
associated with RT.

Among neuronal damage markers (Table 3), CSF tTau levels
inversely correlated with pericentral total RT ($\text{coef} = -28.2, P = 0.017$),
and with ONL-IS thickness in both the foveal ($\text{coef} = -19.5, P = 0.029$) and pericentral region ($\text{coef} = -18.1, P = 0.006$). Of note, we observed consistent negative coefficients for
relations between CSF NFH and RT, but these correlations did not reach statistical significance (i.e., foveal total RT: $\text{coef} = -37.4, P = 0.071$; foveal GCL: $\text{coef} = -6.5, P = 0.070$; foveal ONL-IS: $\text{coef} = -21.5, P = 0.080$; pericentral INL: $\text{coef} = -5.8, P = 0.068$).

For the significant associations between biomarkers and RT,
we performed a sensitivity analysis further adjusting for
ethnicity, which did not alter these results. We additionally
performed a sensitivity analysis excluding the right eye from
the participant with uveitis in the fellow eye, to avoid
confounding on the biomarker profile. This did not alter our
results.

**DISCUSSION**

In this study, we explored whether biomarkers of immune
activation, inflammation, and neuronal injury were associated
with retinal thinning in perinatally HIV-infected children.
Systemic levels of inflammation-associated biomarkers IL-6,
MCP-1, and sICAM-1, and of CSF neuronal damage marker tTau,
were inversely correlated with RT. These findings could
indicate that immune activation, inflammation, vascular
endothelial activation, and neuronal injury occur in parallel
with retinal thinning. These markers may be relevant for
further research to unravel the pathogenesis of retinal
structural changes in pediatric (and adult) HIV.

A possible mechanism by which increased peripheral blood
levels of inflammation-associated markers IL-6, MCP-1, and
sICAM-1 could relate to retinal thinning is impairment of retinal
barrier function. Both MCP-1 and IL-6 have been shown to impair
tight junctions in the BRB, which may render the retina
more vulnerable to viral particles and proinflammatory
cytokines.15 Barrier dysfunction has also been described in
human brain microvascular endothelial cells of the BBB, where
HIV has been shown to upregulate IL-6, MCP-1, and sICAM-1,
facilitating adhesion and migration of monocytes into the
brain.28,29

We found no associations between retinal thinning and CSF
inflammation-associated biomarkers. We hypothesize that this
may be explained by the relatively short half-life of most
cytokines and the larger distance between the retina and CSF
as compared to blood.50 Additionally, immune responses may
differ between the two compartments, which is supported by
the limited concordance between systemic and intrathecal
levels of these markers in our cohort.19 With the sparsity of
pediatric data on CSF biomarkers, further studies are needed to
confirm our findings, and to elucidate how plasma and CSF
immune activation and inflammation relate to each other and
to HIV-associated neuroretinal injury over time. We previously
found that the pathogenesis of neuroretinal thinning may share
common features with that of microstructural white matter
injury in HIV-infected children.4 Thus, investigating systemic
and intrathecal inflammation-associated biomarkers in relation
to white matter microstructure may contribute to our
understanding of the pathogenesis of both cerebral and retinal
injury in pediatric HIV.

Levels of tTau in CSF inversely correlated with thickness of
the foveal and pericentral ONL-IS, and with pericentral total
RT. Tau is a neuronal cytoskeletal protein that, when distorted,
causes neurodegeneration via various pathways, for instance
by accumulation in oligomers and tangles in hyperphosphory-
lated form.31 In HIV-infected adults, elevated tTau levels were
associated with HAND severity, indicating a potential role in
HIV-related neuronal injury.72,53 Studies evaluating Tau in the
retina are scarce in the field of HIV, but tauopathy has been
shown to contribute to retinal injury in various other ocular
and neurodegenerative diseases, including glaucoma and
Alzheimer's disease.19,51 Additionally, in a mouse model of
retinal degeneration, Tau deposits were associated with
degeneration of photoreceptors, with a concomitant reduction
in thickness of the inner and outer nuclear layers, the latter of
which contains photoreceptor cell bodies.54 As the ONL-IS
showed the most prominent thinning in our cohort,5 it is
valuable to further investigate the localization and different
forms of Tau proteins to clarify their exact role in HIV-
associated retinal pathology.

Associations between CSF neuronal damage marker NFH
and retinal thinning were not statistically significant, possibly
due to our study being underpowered. Studies specifically
directing the relevance of NFH in retinal injury associated
with HIV or other neurodegenerative diseases are scarce,
hindering comparison of our results with other findings. It may
be still a marker worth future investigation, as it is thought to
reflect neuronal injury in HIV infection. A study in untreated
HIV-infected adults showed that higher CSF NFH levels were
associated with increased monocyte activation and impaired
processing speed.55 Additionally, a recent study showed that
NFH measured in the vitreous body of the eye was increased
for up to 2 years after non-HIV-related retinal pathology (such
as retinal detachment), confirming that NFH reflects neuronal
degeneration in the retina.56 This technique could be useful
to study the potential role of NFH in HIV, although ethical
considerations considerably limit its use.

Our study does not provide evidence that NFL plays a role
in neuroretinal injury in pediatric HIV, as no associations were
found between retinal thinning and increased blood or CSF
levels of NFL. While CSF NFL has been consistently associated
with severity of HIV disease and HAND in adults,56,57 the
relevance of NFL in pediatric HIV-associated CNS injury remains
less clear due to lack of CSF data in pediatric populations.

Other studies evaluating retinal abnormalities in HIV-
infected adults and children have reported both thinning and
thickening of the macula and peripapillary retinal nerve fiber
layer.5,58,59 It would be interesting to see how these markers of
inflammation, immune activation, and neuronal damage relate
to the RT in different age groups and disease stages, and
whether this can explain some of the observed variation.

While we are the first to explore a potential relationship of
immune activation, inflammation, and neuronal injury with
retinal alterations in perinatally HIV-infected children on long-
term cART, our study was subject to some limitations. Our
small sample size for the regression analyses may have led to
insufficient power to detect relevant correlations. While
adjusting our analyses for age may in part account for variations
in ocular growth and development, the lateral measurement
areas were not adjusted for individual differences in axial
## TABLE 2. Correlations Between Inflammatory Markers and RT in HIV-Infected Children

<table>
<thead>
<tr>
<th></th>
<th>Total RT</th>
<th>GCL</th>
<th>IPL</th>
<th>INL</th>
<th>ONL-IS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foveal</td>
<td>Pericentral</td>
<td>Foveal</td>
<td>Pericentral</td>
<td>Foveal</td>
</tr>
<tr>
<td>Blood plasma, n = 32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CRP</td>
<td>-4.06 (.40)</td>
<td>-0.36 (.95)</td>
<td>-0.75 (.35)</td>
<td>0.46 (.74)</td>
<td>-1.52 (.09)</td>
</tr>
<tr>
<td>IL-6*</td>
<td>-9.56 (.11)</td>
<td>3.83 (.48)</td>
<td>-2.49 (.010†)</td>
<td>1.06 (.55)</td>
<td>-4.40 (&lt;.001†)</td>
</tr>
<tr>
<td>IL-15</td>
<td>-26.32 (.18)</td>
<td>-13.07 (.45)</td>
<td>-5.81 (.07)</td>
<td>-1.19 (.84)</td>
<td>-7.11 (.06)</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>8.58 (.31)</td>
<td>6.79 (.35)</td>
<td>1.27 (.37)</td>
<td>1.10 (.65)</td>
<td>-1.17 (.48)</td>
</tr>
<tr>
<td>IP-10</td>
<td>2.11 (.85)</td>
<td>1.39 (.87)</td>
<td>0.74 (.66)</td>
<td>-0.63 (.85)</td>
<td>-1.71 (.38)</td>
</tr>
<tr>
<td>MCP-1</td>
<td>11.27 (.67)</td>
<td>12.16 (.59)</td>
<td>0.50 (.91)</td>
<td>-6.23 (.40)</td>
<td>-9.67 (.047†)</td>
</tr>
<tr>
<td>sCD14</td>
<td>-9.42 (.43)</td>
<td>-13.39 (.19)</td>
<td>0.84 (.68)</td>
<td>-1.98 (.56)</td>
<td>-0.96 (.68)</td>
</tr>
<tr>
<td>sVCAM-1</td>
<td>-14.63 (.54)</td>
<td>-9.42 (.65)</td>
<td>-0.42 (.92)</td>
<td>1.48 (.83)</td>
<td>-0.89 (.85)</td>
</tr>
<tr>
<td>sICAM-1</td>
<td>-14.11 (.61)</td>
<td>9.80 (.69)</td>
<td>-5.61 (.22)</td>
<td>3.75 (.64)</td>
<td>-10.48 (.042†)</td>
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<tr>
<td>CSE n = 24‡</td>
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</tr>
<tr>
<td>CRP</td>
<td>-5.52 (.45)</td>
<td>0.36 (.95)</td>
<td>-1.30 (.28)</td>
<td>1.33 (.48)</td>
<td>-1.75 (.23)</td>
</tr>
<tr>
<td>IL-6</td>
<td>5.91 (.72)</td>
<td>-2.96 (.82)</td>
<td>-0.45 (.87)</td>
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<td>-0.25 (.94)</td>
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<tr>
<td>IFN-γ*</td>
<td>-5.52 (.54)</td>
<td>-7.09 (.51)</td>
<td>-0.22 (.88)</td>
<td>-3.31 (.14)</td>
<td>0.69 (.67)</td>
</tr>
<tr>
<td>IP-10*</td>
<td>-0.46 (.96)</td>
<td>1.46 (.81)</td>
<td>-0.57 (.70)</td>
<td>-1.34 (.56)</td>
<td>-1.09 (.54)</td>
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<tr>
<td>MCP-1*</td>
<td>-6.60 (.46)</td>
<td>4.43 (.54)</td>
<td>-2.19 (.13)</td>
<td>0.40 (.87)</td>
<td>-1.96 (.27)</td>
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<td>sCD14‡</td>
<td>-2.32 (.78)</td>
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<td>0.03 (.98)</td>
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<td>0.85 (.62)</td>
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<td>sVCAM-1</td>
<td>-18.21 (.32)</td>
<td>-6.82 (.65)</td>
<td>-2.90 (.34)</td>
<td>3.11 (.52)</td>
<td>-2.02 (.59)</td>
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<td>sICAM-1</td>
<td>-34.58 (.16)</td>
<td>-4.46 (.85)</td>
<td>-7.20 (.07)</td>
<td>5.74 (.38)</td>
<td>-8.90 (.07)</td>
</tr>
</tbody>
</table>

This table shows the results of the mixed effects regression analyses, evaluating associations between retinal layers and inflammation-associated biomarkers. According to distribution, variables are log pg/mL, or dichotomized using a median split where specified. Data are presented as coefficient (P).

* Variable dichotomized using median split.
† P < 0.05.
‡ n = 24 for sCD14 and n = 22 for all other biomarkers.
Table 3. Correlations Between Neuronal Damage Markers and RT in HIV-Infected Children

<table>
<thead>
<tr>
<th>Biomarker</th>
<th>Serum</th>
<th>CSF</th>
<th>NFL</th>
<th>NFH</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Foveal</td>
<td>Pericentral</td>
<td>Foveal</td>
<td>Pericentral</td>
</tr>
<tr>
<td></td>
<td>7.15 (2.43)</td>
<td>0.95 (8.27)</td>
<td>0.83 (8.27)</td>
<td>11.3 (3.33)</td>
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<td></td>
<td>3.88 (8.27)</td>
<td>1.95 (5.99)</td>
<td>1.95 (5.99)</td>
<td>3.86 (7.99)</td>
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<td></td>
<td>0.81 (0.44)</td>
<td>1.95 (5.99)</td>
<td>0.85 (5.99)</td>
<td>0.85 (5.99)</td>
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<tr>
<td></td>
<td>1.01 (2)</td>
<td>0.38 (0.78)</td>
<td>0.38 (0.78)</td>
<td>1.01 (2)</td>
</tr>
<tr>
<td></td>
<td>0.95 (8.27)</td>
<td>1.95 (5.99)</td>
<td>1.95 (5.99)</td>
<td>3.86 (7.99)</td>
</tr>
<tr>
<td></td>
<td>0.83 (8.27)</td>
<td>1.95 (5.99)</td>
<td>1.95 (5.99)</td>
<td>3.86 (7.99)</td>
</tr>
<tr>
<td></td>
<td>11.3 (3.33)</td>
<td>1.63 (7.7)</td>
<td>-0.01 (2)</td>
<td>0.80 (4.4)</td>
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<tr>
<td></td>
<td>3.88 (8.27)</td>
<td>1.95 (5.99)</td>
<td>1.95 (5.99)</td>
<td>3.86 (7.99)</td>
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This table shows the results of the mixed-effects regression analyses, evaluating associations between retinal layers and neuronal damage markers in serum and CSF. Data are presented as coefficient (P = n). Variable dichotomized using median split.† p < 0.05.

In conclusion, the current study shows inverse relationships between RT and systemic inflammation-associated markers IL-6, MCP-1, and sICAM-1, and CSF neuronal damage marker tTau, in a cohort of long-term clinically and virally controlled HIV-infected children. Further research is needed to ascertain whether any of these markers play a role in the pathogenesis of retinal thinning. To test this hypothesis, the relationship between inflammation-associated biomarkers, BRB integrity, and neuronal injury could be investigated on a microstructural level, using immunohistochemical analysis or in vivo localization imaging techniques. Longitudinal studies are needed to evaluate how inflammation-associated and neuronal biomarkers relate to the clinical course and severity of retinal deficits over time. Considering the association between retinal and microstructural white matter injury, this could not only contribute to our understanding of the pathogenesis of retinal thinning, but also of cerebral and neurocognitive deficits in pediatric HIV. These are essential steps toward better treatment and prevention of cerebral and retinal injury in treated HIV-infected children now surviving into adulthood.

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