Association of Birth Weight with Peripapillary Retinal Nerve Fiber Layer Thickness in Adulthood—Results from a Population-Based Study

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PURPOSE. Low birth weight is associated with altered retinal development in childhood, including reduced peripapillary retinal nerve fiber layer (pRNFL) thickness. However, to the best of our knowledge, no population-based study has analyzed the relationship of low birth weight to pRNFL thickness in adulthood. The purpose of this study was to investigate whether birth weight has a long-term effect on pRNFL thickness in adulthood.

METHODS. In the German population-based Gutenberg Health Study (GHS), participants were examined with spectral-domain optical coherence tomography using a peripapillary scan and automated measurement of pRNFL thickness as a global parameter and in six sectors. The association between self-reported birth weight and the different pRNFL sectors were analyzed with multivariable linear regression, adjusted for potential confounders including sex, age, axial length, self-reported age-related macular degeneration, and glaucoma.

RESULTS. In 3,028 participants, self-reported birth weight was documented and pRNFL measurements were successfully performed (1632 females, ages 54.9 ± 10.0 years). After adjustment for several confounders in the multivariable model, a positive association was observed between birth weight and pRNFL thickness in the global sector (β = 0.13 μm/100 g; 95% CI, 0.08–0.18; P < 0.001; R² = 0.007) and especially in the inferotemporal sector (β = 0.22 μm/100 g; 95% CI, 0.15–0.29; P < 0.001; R² = 0.008) and inferonasal sector (β = 0.28 μm/100 g; 95% CI, 0.17–0.39; P < 0.001; R² = 0.005).

CONCLUSIONS. Our data show that there is a weak relationship between birth weight and pRNFL thickness in adulthood. This weak association is particularly present in the inferior part of the optic nerve head. Therefore, low birth weight may have an impact on optic nerve head development and potentially on ocular disease development.

Keywords: birth weight, peripapillary retinal nerve fiber layer, optic nerve, anatomy, epidemiology

During embryologic development, the optic nerve contains approximately 2 million axons at the end of the first trimester, peaks at 4 million, and reaches its final number of about 1 million at the end of the second trimester.1 Premature birth affects the embryologic development of central nervous tissues2 and leads to different cortical volumes of the cerebral of former preterm individuals.3,4 Adverse development of the immature brain and damage of the optic radiation might lead to a retrograde trans-synaptic degeneration of retinal ganglion cells.5 Rothman and colleagues6 observed a correlation between brain structure and peripapillary retinal nerve fiber layer (pRNFL)
thinning in preterm infants (gestational age < 32 weeks). Scarc population-based data exist regarding the association of low birth weight and pRNFL in childhood, whereas to our knowledge no population-based data exist for this relationship in adulthood.

Worldwide, every seventh child is born with low birth weight (<2500 g), accounting for about 20.5 million low-birth-weight newborns every year.9 Because the number of low-birth-weight newborns is increasing, understanding potential long-term effects becomes more important.

Low birth weight is a proxy measure of prenatal growth restriction, preterm birth, and disorders of ocular growth development in childhood, including reduced peripapillary retinal nerve fiber layer thickness. The retinal nerve fiber layer of the optic nerve head is part of the central nervous system and can be non-invasively measured with spectral-domain optical coherence tomography (SD-OCT). Perinatal factors associated with reduced pRNFL thickness in childhood include low birth weight,9–11 low gestational age at birth,10,12 and retinopathy of prematurity (ROP).13 In a recent report, we demonstrated that low birth weight and low gestational age are related to a thinner pRNFL, and postnatal ROP occurrence is linked to an isolated pRNFL increase of the temporal sector in children 4 to 10 years of age. In addition, we found an association between thinner pRNFL and reduced visual acuity.10 In the population-based Copenhagen Child Cohort 2000 Eye Study, thinner pRNFL thickness was found in former low-birth-weight infants (<2500 g; 11 to 12 years of age at the time of the study) compared to former normal birth weight infants (≥2500 g).7

Thinner pRNFL is associated with various optic neuropathies, particularly glaucoma, which is one of the main eye diseases causing visual impairment and blindness in Western countries.14 Therefore, gaining knowledge about the factors affecting the pRNFL is of importance and may contribute to a better understanding of potential risk factors for glaucoma.

This study analyzed the association of birth weight with pRNFL thickness in adults 40 to 80 years of age. We hypothesized that low birth weight is associated with a thinner pRNFL in adulthood.

**Materials and Methods**

**Study Population**

The interdisciplinary Gutenberg Health Study (GHS) is a prospective, population-based, observational, single-center cohort study conducted in the Rhine-Main region of Western Germany (Rhineland-Palatinate).35 Recruitment of the GHS sample was performed between 2007 and 2012 for baseline examination of participants between 35 and 74 years of age. The sample was randomly drawn from local governmental registry offices, where every resident is mandatorily registered and stratified by sex, residence (urban or rural), and decades of age. Every selected resident was invited by mail with follow-up by telephone. The recruitment efficacy was 55.5%.

The present analysis includes subjects of the 5-year follow-up examination who underwent SD-OCT examination between 2012 and 2017. Overall, 12,423 GHS participants (82.8% of all participants) had a 5-year follow-up examination. These participants had a medical history interview, in addition to a detailed ophthalmological examination, including measurements of peripapillary retinal thickness measurement with SD-OCT.

Written informed consent was obtained from all study participants prior to study participation, and the GHS complied with good clinical practices, good epidemiological practices, and the tenets of the Declaration of Helsinki. The study protocol and study documents were approved by the local ethics committee of the Medical Chamber of Rhineland-Palatinate, Germany (reference no. 837.020.07).

**Birth Weight**

In this cross-sectional analysis, only subjects with available self-reported birth weights were included. Further inclusion criteria were measurement of objective refraction, corneal curvature, and the pRNFL in at least one eye. The exclusion criterion was a history of ocular injury. The participants were asked to review their records or family albums for documented birth weights; based on this information, they were divided into the following birth weight groups: group 1, low birth weight (<2500 g); group 2, normal birth weight (2500–4000 g); and group 3, high birth weight (>4000 g), as reported earlier.16–19 Additionally, participants with birth weights below 1000 g and above 6000 g were excluded, as these self-reported data were suspected to be unreliable.

**Ophthalmologic Examination**

In brief, the ophthalmological examination included measurement of visual acuity and refraction with a Humphrey HARK 599 Autorefractor Keratometer (Carl Zeiss Meditec, Jena, Germany); intraocular pressure measurement with a NT-2000 non-contact tonometer (Nidek, Tokyo, Japan); biometry using a Lenstar LS900 optical biometer (Haag-Streit, Bern, Switzerland); and non-mydriatic fundus photography and imaging of the optic nerve head using the Spectralis SD-OCT system (Heidelberg Engineering, Heidelberg, Germany).20 The spherical equivalent was calculated by adding the spherical correction value to half the cylinder value.

Ocular biometry was performed with the Lenstar 900 optical biometer, as described earlier.18 Furthermore, age-related macular degeneration (AMD) was surveyed. Glaucoma was defined according to the definition proposed by Foster et al.,21 the International Society of Geographical and Epidemiological Ophthalmology (ISGEO) definition, with a few adjustments with regard to visual field testing (using frequency doubling technology perimetry), as described before.22 In brief, the vertical cup-to-disc ratio (vCDR) was determined in each eye, and individual cutoff values with respect to optic disc size were computed. Eyes with a vCDR ≥97.5th percentile (of a normal population without visual field defect) with a visual field defect, eyes with a vCDR above the 99.5th percentile, or eyes with a rim width ≤0.1 were defined as glaucoma, if there was no other explanation for these measurements investigated by two masked glaucoma specialists.

**Optical Coherence Tomography**

With SD-OCT, a non-invasive and non-contact device uses light reflection of the various retinal tissues to generate cross-sectional two- and three-dimensional images of the retina. For the present study, a circular peripapillary scan of 12° diameter centered on the optic disc with eye tracking.
was conducted with a standard 7.7-mm corneal curvature and ametropia of 0 diopter (dpt). Heidelberg Eye Explorer (HEXYP) software was used for automatic segmentation of pRNFL thickness. Software algorithms calculated global and sectorial pRNFL thickness (global, superonasal, nasal, inferonasal, inferotemporal, temporal, superotemporal) from the data provided by the circle scans. We adjusted the pRNFL measures for ocular magnification by incorporating corneal curvature and spherical equivalent, the same parameters used in the HEXYP software for adjustment of ocular magnification (personal communication with Heidelberg Engineering).

All SD-OCTs were performed in non-mydriatic eyes. Also, all scans were checked by an experienced investigator and were excluded in case of decentralization or layer segmentation errors. In addition, scan quality was checked and only high-quality images with ideal centration and a high signal strength of >15 dB (ranging from 0 for no signal to 40 for an excellent signal) were selected for this study.

### Covariates

The following parameters were included in the multivariable model because they were considered to be associated with the pRNFL, based on the medical literature and were judged as being potentially associated with birth weight: (1) age, (2) sex, (3) axial length, (4) age-related macular degeneration, and (5) glaucoma (ISGEO definition).

### Statistical Analysis

The main outcome measures were pRNFL thickness in the global sector and in the six subsectors (superonasal, nasal, inferonasal, inferotemporal, temporal, and superotemporal). A comparison of characteristics of participants with available self-reported birth weights versus participants without self-report birth weights was conducted. The distribution of low, normal, and high birth weights in our cohort was compared to reported birth weight data in the medical literature and to data of the German Federal Statistical Office, as reported earlier.

Descriptive statistics were computed for the main outcome measures. Absolute and relative frequencies were calculated for dichotomous parameters. The mean and standard deviation were calculated for approximately normally distributed data; otherwise, the median and interquartile range were used.

Both eyes of an individual were included into our analyses, if sufficient peripapillary OCT imaging was available, and linear regression models with general estimating equations were used to assess associations and to account for correlations between both eyes of an individual. In model 1, the main outcome measures were related to birth weight as independent variable; in model 2, the associations were adjusted for age, sex, axial length, age-related macular degeneration, and glaucoma (ISGEO definition). Furthermore, a sensitivity analysis was carried out including only subjects with an axial length between 23.00 mm (25th percentile) and 24.4 mm (75th percentile). To investigate the disproportion of subjects between the three birth weight groups, we performed a subanalysis with equal proportions of subjects in each birth weight group. Another sensitivity analysis was performed on all participants with self-reported birth weights, including those reporting birth weights < 1000 g and > 6000 g, as well.

All models were computed in a first step that included birth weight as a continuous variable and in a second step that included birth weight as a categorical variable (birth weight < 2500 g, birth weight 2500–4000 g, and birth weight > 4000 g).

The data were analyzed with R version 3.5.2. This was an exploratory study, and no adjustment for multiple testing was carried out.

### RESULTS

#### Participant Characteristics

Of the 15,010 participants at baseline, 12,423 were examined at the 5-year follow-up. Of these, 6140 had successful SD-OCT measurements of at least one eye. Missing measurements were attributed to organizational issues. Of these, in turn, 3679 had documented self-reported birth weight data. Eighteen participants were excluded due to implausible birth weight data (>6000 g or <1000 g), and 633 participants were excluded due to missing data on corneal curvature or spherical equivalent measurement or due to medical history of eye injury.

The participants’ characteristics are presented in Table 1. Participants mean age was 54.9 ± 10.0 years, and 53.9% (n = 1632) were female. Birth weight below 2500 g (group 1) was reported by 173 participants, birth weight between 2500 g and 4000 g (group 2) was reported by 2499 participants, and a birth weight above 4000 g (group 3) was reported by 356 participants (Table 1). Descriptive data on global pRNFL and for each sector are presented in Table 2. The low-birth-weight group showed the lowest pRNFL measures in the various sectors compared to the normal-weight and high-birth-weight groups.

#### Item Non-Responder Analysis

Out of the 12,423 participants who attended the follow-up examination, 9,395 did not provide birth weight data, had no pRNFL measurement, or did not meet the inclusion criteria. Participants with available information were younger and more likely to be female compared to participants with missing information. In addition, they were less likely to have hypertension and diabetes and their ocular parameters were similar. In particular, global pRNFL thickness was similar between participants with and without birth weight information. Participants without OCT data were slightly younger and had similar birth weights.

### Birth Weight as Continuous Variable

Global pRNFL was thinner in adults with low birth weight in unadjusted analyses (model 1: β = 0.12 μm/100 g; 95% CI, 0.07–0.17; P < 0.001) and in adjusted analyses after consideration of age, sex, axial length, age-related macular degeneration, and glaucoma (model 2: β = 0.13 μm/100 g; 95% CI, 0.08–0.18; P < 0.001). Furthermore, low birth weight was associated with thinner pRNFL in the inferotemporal sector (model 2: β = 0.22 μm/100 g; 95% CI, 0.15–0.29; P < 0.001) and inferonasal sector (model 2: β = 0.28 μm/100 g; 95% CI, 0.17–0.39; P < 0.001). The superotemporal sector (model 2: β = 0.09 μm/100 g; 95% CI, 0.01–0.19; P = 0.024), the superonasal sector (model 2: β = 0.15 μm/100 g; 95% CI, 0.05–0.25; P = 0.004), and the nasal sector (model 2: β
Table 1. Characteristics of the Study Sample (N = 3028)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Birth Weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;2500 g</td>
<td>2500–4000 g</td>
</tr>
<tr>
<td>Participants, n</td>
<td>173</td>
<td>2499</td>
</tr>
<tr>
<td>Female, n (%)</td>
<td>115 (66.5%)</td>
<td>1389 (55.6%)</td>
</tr>
<tr>
<td>Age (y), mean ± SD</td>
<td>56.1 ± 11.0</td>
<td>54.6 ± 9.9</td>
</tr>
<tr>
<td>Birth weight (g), mean ± SD</td>
<td>2042 ± 356</td>
<td>3343 ± 396</td>
</tr>
<tr>
<td>Body mass index (kg/m²), mean ± SD</td>
<td>27.1 ± 5.3</td>
<td>26.9 ± 5.0</td>
</tr>
<tr>
<td>Presence of arterial hypertension, n (%)</td>
<td>79 (45.7)</td>
<td>1042 (41.7)</td>
</tr>
<tr>
<td>logMAR OD, median (25%, 75% percentiles)</td>
<td>0.1 (0.0, 0.2)</td>
<td>0.1 (0.0, 0.1)</td>
</tr>
<tr>
<td>logMAR OS, median (25%, 75% percentiles)</td>
<td>0.1 (0.0, 0.2)</td>
<td>0.1 (0.0, 0.1)</td>
</tr>
<tr>
<td>IOP OD (mm Hg), mean ± SD</td>
<td>14.8 ± 3.1</td>
<td>14.6 ± 2.9</td>
</tr>
<tr>
<td>IOP OS (mm Hg), mean ± SD</td>
<td>15.0 ± 3.1</td>
<td>14.7 ± 2.8</td>
</tr>
<tr>
<td>Spherical equivalent OD (dpt), median (25%, 75% percentiles)</td>
<td>-0.38 (-1.88, 0.75)</td>
<td>-0.25 (-1.38, 0.50)</td>
</tr>
<tr>
<td>Spherical equivalent OS (dpt), median (25%, 75% percentiles)</td>
<td>-0.25 (-1.75, 0.75)</td>
<td>-0.25 (-1.38, 0.62)</td>
</tr>
<tr>
<td>Axial length OD (mm), mean ± SD</td>
<td>23.6 ± 1.3</td>
<td>23.8 ± 1.2</td>
</tr>
<tr>
<td>Axial length OS (mm), mean ± SD</td>
<td>23.5 ± 1.2</td>
<td>23.7 ± 1.2</td>
</tr>
<tr>
<td>Corneal radius OD (mm), mean ± SD</td>
<td>7.68 ± 0.26</td>
<td>7.77 ± 0.28</td>
</tr>
<tr>
<td>Corneal radius OS (mm), mean ± SD</td>
<td>7.68 ± 0.26</td>
<td>7.77 ± 0.28</td>
</tr>
<tr>
<td>Eye disease present</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMD, n (%)</td>
<td>5 (2.9)</td>
<td>31 (1.2)</td>
</tr>
<tr>
<td>Glaucoma, n (%)</td>
<td>3 (1.9)</td>
<td>20 (0.9)</td>
</tr>
</tbody>
</table>

Data are from the population-based Gutenberg Health Study (2012–2017). IOP, intraocular pressure.

Table 2. Measurements of pRNFL Thickness by Birth Weight Groups

<table>
<thead>
<tr>
<th>pRNFL</th>
<th>Birth Weight &lt; 2500 g (n = 173)</th>
<th>Birth Weight 2500–4000 g (n = 2499)</th>
<th>Birth Weight &gt; 4000 g (n = 356)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right eye</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>95.9 ± 9.7</td>
<td>97.8 ± 9.7</td>
<td>98.3 ± 9.4</td>
</tr>
<tr>
<td>Superotemporal</td>
<td>133.4 ± 17.7</td>
<td>135.9 ± 18.3</td>
<td>136.3 ± 17.9</td>
</tr>
<tr>
<td>Temporal</td>
<td>70.6 ± 11.3</td>
<td>72.6 ± 13.6</td>
<td>71.4 ± 13.4</td>
</tr>
<tr>
<td>Inferotemporal</td>
<td>142.5 ± 19.5</td>
<td>146.3 ± 20.0</td>
<td>144.9 ± 20.7</td>
</tr>
<tr>
<td>Inferonasal</td>
<td>109.7 ± 24.3</td>
<td>110.9 ± 23.8</td>
<td>112.8 ± 24.2</td>
</tr>
<tr>
<td>Nasal</td>
<td>71.0 ± 13.9</td>
<td>73.1 ± 14.6</td>
<td>74.5 ± 14.7</td>
</tr>
<tr>
<td>Superonasal</td>
<td>98.3 ± 21.6</td>
<td>97.8 ± 19.1</td>
<td>99.8 ± 19.6</td>
</tr>
<tr>
<td>Left eye</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>94.4 ± 10.7</td>
<td>97.7 ± 9.4</td>
<td>98.7 ± 10.0</td>
</tr>
<tr>
<td>Superotemporal</td>
<td>133.2 ± 19.0</td>
<td>134.7 ± 18.5</td>
<td>134.3 ± 18.1</td>
</tr>
<tr>
<td>Temporal</td>
<td>67.7 ± 12.1</td>
<td>68.8 ± 12.7</td>
<td>67.5 ± 12.1</td>
</tr>
<tr>
<td>Inferotemporal</td>
<td>138.5 ± 19.9</td>
<td>144.4 ± 20.7</td>
<td>143.7 ± 20.7</td>
</tr>
<tr>
<td>Inferonasal</td>
<td>107.1 ± 26.2</td>
<td>112.3 ± 23.5</td>
<td>116.2 ± 25.0</td>
</tr>
<tr>
<td>Nasal</td>
<td>67.2 ± 16.1</td>
<td>71.8 ± 14.5</td>
<td>74.2 ± 14.6</td>
</tr>
<tr>
<td>Superonasal</td>
<td>106.0 ± 21.2</td>
<td>108.2 ± 20.5</td>
<td>111.9 ± 22.1</td>
</tr>
</tbody>
</table>

Data are from the population-based Gutenberg Health Study (2012–2017).

= 0.18 μm/100 g; 95% CI, 0.00–0.35; P = 0.048) revealed a weaker association, and the other sectors showed no association in the adjusted model (Table 3). Scatterplots of birth weight with pRNFL thickness of the global sector, nasal inferior sector, and temporal inferior sector are displayed in the Figure. Pearson’s correlation coefficients of global and sectoral pRNFL with birth weight as the continuous variable for the right and left eye are presented in the Supplementary Table.

Birth Weight Categorized into Low, Normal, and High Birth Weight

When analyzing birth weights categorized as low, normal, or high, the global pRNFL thickness was smaller in the low-birth-weight group compared to the normal-birth-weight group in the adjusted analysis (model 2: β = −2.20 μm; 95% CI, −3.47 to −0.92; P < 0.001), whereas the pRNFL was thicker in the high-birth-weight group compared to the normal-birth-weight group (model 2: β = 1.06 μm; 95% CI, 0.21–1.91; P = 0.015) (Table 4).

In adjusted analyses, the low-birth-weight group showed a thinner pRNFL in the inferotemporal sector (β = −3.44 μm; 95% CI, −5.26 to −1.61; P < 0.001), but the other sectors showed no association.

Among the high-birth-weight participants, a thicker pRNFL was observed in the inferotemporal sector (model 2: β = 2.43 μm; 95% CI, 1.13–3.72; P < 0.001), inferonasal (model 2: β = 3.98 μm; 95% CI, 1.85–6.11; P < 0.001), and superonasal (model 2: β = 2.73 μm; 95% CI, 0.80–4.66; P = 0.006) sectors compared to normal-birth-weight subjects. No relationship was observed in the other sectors.
### Table 3. Associations of Global and Sectoral pRNFLs with Birth Weight as Continuous Variable (N = 3028)

<table>
<thead>
<tr>
<th>pRNFL</th>
<th>Model 1†</th>
<th>Model 2‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β (95% CI)</td>
<td>P</td>
</tr>
<tr>
<td>Global</td>
<td>0.12 (0.07, 0.17)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Superotemporal</td>
<td>0.12 (0.04, 0.21)</td>
<td>0.005</td>
</tr>
<tr>
<td>Temporal</td>
<td>0.00 (–0.06, 0.06)</td>
<td>1.0</td>
</tr>
<tr>
<td>Inferotemporal</td>
<td>0.19 (0.12, 0.26)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Inferonasal</td>
<td>0.22 (0.10, 0.33)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Nasal</td>
<td>0.14 (–0.05, 0.31)</td>
<td>0.11</td>
</tr>
<tr>
<td>Supernasal</td>
<td>0.14 (0.04, 0.24)</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Data are from the population-based Gutenberg Health Study (2012–2017). Linear regression analysis using generalized estimating equations to control for correlations between right and left eyes was applied.

† Model 1 is crude model without adjustment.
‡ Model 2 is adjusted for sex, age, axial length, age-related macular degeneration, and glaucoma (ISGEO definition).
‡ Change of $R^2$ when including birth weight as an additional parameter in the multivariable model.

### Table 4. Associations of Global and Sectorial pRNFL with Birth Weight Groups (N = 3028)

<table>
<thead>
<tr>
<th>pRNFL</th>
<th>Model 1†</th>
<th>Model 2‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β (95% CI)</td>
<td>P</td>
</tr>
<tr>
<td>Global</td>
<td>–2.57 (–3.88, –1.25)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>0.66 (–0.20, 1.51)</td>
<td>0.135</td>
</tr>
<tr>
<td>Superotemporal</td>
<td>–2.42 (–4.71, –0.13)</td>
<td>0.038</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>–0.35 (–1.95, 1.25)</td>
<td>0.668</td>
</tr>
<tr>
<td>Temporal</td>
<td>–0.90 (–2.40, 0.60)</td>
<td>0.24</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>–1.11 (–2.29, 0.07)</td>
<td>0.064</td>
</tr>
<tr>
<td>Inferotemporal</td>
<td>–3.63 (–5.54, –1.73)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>2.03 (0.72, 3.33)</td>
<td>0.002</td>
</tr>
<tr>
<td>Inferonasal</td>
<td>–3.17 (–6.39, 0.06)</td>
<td>0.054</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>2.92 (0.71, 5.13)</td>
<td>0.010</td>
</tr>
<tr>
<td>Nasal</td>
<td>–4.38 (–9.16, 0.39)</td>
<td>0.072</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>–0.22 (–3.69, 3.24)</td>
<td>0.90</td>
</tr>
<tr>
<td>Superonasal</td>
<td>–1.42 (–4.19, 1.34)</td>
<td>0.314</td>
</tr>
<tr>
<td>Birth weight &lt; 2500 g</td>
<td>Reference</td>
<td>—</td>
</tr>
<tr>
<td>Birth weight &gt; 4000 g</td>
<td>2.45 (0.55, 4.36)</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Data are from the population-based Gutenberg Health Study (2012–2017). Linear regression analysis using generalized estimating equations to control for correlations between right and left eyes.

† Model 1 is crude model without adjustment.
‡ Model 2 is adjusted for sex, age, axial length, age-related macular degeneration, and glaucoma (ISGEO definition).
‡ Change of $R^2$ when including birth weight as an additional parameter in the multivariable model.

### Sensitivity Analyses

Equal proportions of subjects in each group revealed comparable results. Similar associations were observed when study participants with birth weights < 1000 g or > 6000 g were included, as well, and when analyzing subjects with an axial length of 23.00 to 24.4 mm.

### Discussion

In this study, low birth weight was associated with a thinner pRNFL in adulthood. These results provide new insights into the long-term effects of low birth weight on optic nerve morphology, indicating that pre- and perinatal growth restrictions are connected to altered optic nerve morphology.
al.31 and colleagues also demonstrated that low birth weight
resulted in ganglion cell loss with resulting visual field defects.
the optic nerve head, such as glaucoma, as well as retinal
disorders such as glaucoma. However, it is still unclear whether higher pRNFL thick-
ness has a protective effect against nerve diseases involving
the retina.

Our results are in line with previous reports on
persons with lower birth weights showed a thinner pRNFL in the global measurement and
in the nasal inferior and temporal inferior sectors.

In a large population-based study of 1323 children 11 to
12 years of age (Copenhagen Child Cohort 2000 Eye Study),
the pRNFL was 3.5 μm thinner in low-birth-weight children
(<2500 g) compared to normal-birth-weight children (≥2500 g),
a finding comparable to the pRNFL differences found in
the present study.

Strengths and Limitations

Forty-four percent of the study participants did not provide
self-reported birth weight data. Participants with missing
birth weight information were generally younger and more
often female. When participants with self-reported birth
weight data were compared to participants without birth
weight data, only small differences were observed in ocular
parameters after adjusting for sex and age. Consequently, we
assume that our results can be generalized to the underlying
German population.

A major restriction is that self-reported birth weight data
could not be validated by reviewing birth records. To ensure
the validity of the self-reported birth weight data, every
subject was requested to look for documented birth weight
data in their personal records or family albums; however,
these associations are long lasting and persist into adulthood.
Our study offers a first hint that the pRNFL is altered in
adulthood due to low birth weight. Furthermore, our finding
of a thinner pRNFL, particularly in the inferior sector, may
be relevant, as in glaucoma patients pRNFL changes manifest
in the inferior sectors first,34 with a conspicuous ISNT rule,
leading to initial superior Bjerrum scotoma.36 Additionally,
progression of glaucoma is most frequently located in
the inferotemporal sector of the pRNFL,34 and pRNFL thin-
ing is linked to several optic neuropathies.34,37–39 Consequently,
low birth weight may be a previously unknown risk
factor, among others, predisposing for these diseases, includ-
ing glaucoma. This suggestion should be explored further
to identify fetal origins of important adult eye diseases.
However, it has to be mentioned that our statistical model
explained only small amounts of the variance in the pRNFL
(R² = 0.007, weak association), and it is unclear whether our
findings have a clinical impact or whether the changes we
observed are of only subclinical importance.

Peripapillary RNFL and Birth Weight

Figure. Scatterplot of birth weight with pRNFL thickness of the
(A) global sector, (B) nasal inferior sector, and (C) temporal inferior sector
in the Gutenberg Health Study (N = 3028). Participants with lower birth weights showed a thinner pRNFL in the global measurement and
in the nasal inferior and temporal inferior sectors.

Beyond childhood and adolescence, with particular impact
on the inferior part of the optic disc. This may be of clinical
relevance, as early signs of glaucoma include an alteration
of the ISNT (inferior ≥ superior ≥ nasal ≥ temporal) rule,28
and low birth weight might be linked to optic neuropathies
such as glaucoma.

Our results are in line with previous reports on
former preterm and/or low-birth-weight infants7,9,10,12,13
and expand previous knowledge into adulthood. The Wies-
baden Prematurity Study found that a thinner pRNFL was
related to low birth weight and low gestational age, whereas
ROP was linked to isolated thickening of the temporal sector.
The authors concluded that the more preterm the infants,
the greater the alteration in the pRNFL.10

However, other authors have observed that the pRNFL is
thinner even in former late-preterm29 and full-term30 infants
when they had a birth weight below the 10th percentile,
which agrees with the data of Pueyo et al.11 Akerblom et
al.31 and colleagues also demonstrated that low birth weight
was linked to a thinner pRNFL in a sample of former preterm
infants.

In former preterm low-birth-weight infants is connected
with altered brain structure and impaired neurologic
development. Other studies reported an association of pRNFL
damage with reduced visual acuity10 and impaired neurode-
velopmental outcome35 in former low-birth-weight individ-
uals. To our knowledge, no data exist regarding whether
these associations are long lasting and persist into adulthood.
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allow further stratification of the analyses. Previous studies in children have particularly recruited former extreme-low-birth-weight infants, which is in contrast to the population-based approach of the GHS study. As a result, our data reflect the influence of low birth weight on the pRNFL in the general population, rather than the effect of prematurity, which may differ from our findings. Analyses of our model fits show that only a small amount of the pRNFL variation can be explained by our statistical models, including birth weight data. Furthermore, the disproportionality in subjects among the birth weight groups could lead to a distortion, so we performed sensitivity analyses.

Strengths of the study are the population-based design and the large sample size. In addition, study investigators were blinded to birth weight data, and examinations were carried out with strict standard operating procedures.

**Summary**

In summary, our results highlight the long-term effects of low birth weight on optic nerve morphology beyond childhood, indicating that low birth weight is a risk factor for a thinner pRNFL in adulthood. Our results suggest that adult pRNFL morphology has its origin in early life; thus, there is the possibility that low birth weight may predispose for optic neuropathies accompanied by pRNFL alteration.

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This analysis presents clinical data regarding a large-scale, population-based cohort with ongoing follow-up examinations. This project represents a major scientific effort that maintained high methodological standards and followed detailed guidelines for analysis and publication to ensure sound scientific analyses at the highest level. The data are not available to the scientific community outside the established and controlled workflows and algorithms. To meet the general principle of verification and reproducibility of scientific findings, we offer access to our data through a local database at any time upon request, in accordance with the ethics vote. The GHS steering committee, which includes a member of each involved department and the coordinating principal investigator of the Gutenberg Health Study (P.S.W.), convenes once a month. The steering committee decides on internal and external access by researchers and use of the data and biomaterials based on a research proposals supplied by the researchers. Interested researchers can make their requests to the coordinating PI of the Gutenberg Health Study (philipp.wild@uni-medizin-mainz.de).

More detailed contact information is available at the homepage of the GHS (www.gutenberghealthstudy.org).

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**References**


