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Population-Based Normative Reference for Retinal Microvascular Atlas

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Objective: To establish the normative range of a comprehensive set of retinal vascular measurements to better understand their value as biomarkers for assessing ocular and systemic health.

Design: Cross-sectional study.

Participants: The study included 10 151 healthy participants from the UK Biobank.

Methods: Retina-based Microvascular Health Assessment System software was used to extract retinal vascular measurements, including caliber, complexity, density, branching angle, and tortuosity, differentiating between arteries and veins and between the macula and retinal periphery. In addition, we explored relationships between those measurements and health metrics, including age, systolic blood pressure (SBP), body mass index, glycated hemoglobin, and intraocular pressure.

Main Outcome Measures: We reported the population normative range for 114 retinal vascular measurements, further stratified by sex and age.

Results: The mean values of central retinal artery equivalent and central retinal vein equivalent (CRVE) were 152 (standard deviation = 14.9) μm and 233 (21.5) μm, respectively. The mean value of fractal dimension (FD) was 1.77 (0.032), with arterial FD 1.53 (0.039) and venular FD 1.56 (0.025). Age and SBP showed the strongest associations with most retinal parameters among health metrics. Central retinal artery equivalent, CRVE, density, and complexity decreased with increasing age and SBP. Changes in arterial measurements with age and SBP were generally greater than those in venous measurements. Generalized additive models further revealed that observed associations were mainly linear.

Conclusions: By establishing population normative data for a comprehensive set of retinal vascular measurements, our study enables quantifiable approaches to better understand retinal vascular changes.

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The retina is unique as a segment of the vascular system, permitting direct, noninvasive visualization. It has been widely studied to understand the link between ocular manifestations and systemic disease since the invention of direct ophthalmoscopy in 1851.[1] While previous research has devoted considerable attention to studying the retinal vascular network and how it reflects systemic health, the scope of work has been limited by the labor-intensive nature of manual labeling. In recent decades, advances in artificial intelligence have accelerated progress in assessing systemic health through characterizing the retinal vascular geometry.[2–5]

Increasing evidence shows that the retinal vascular features are indicative of various systemic diseases, including hypertension, diabetes, cardiovascular and neurodegenerative diseases, and even mortality risk.[6–9] The convenience, noninvasive nature, and affordability of fundus photography make it a valuable tool for risk assessment in these and other health conditions, allowing more timely intervention. Population normative data on retinal vascular features provide a valuable foundation for studying retinal vascular alterations.

Existing studies, generally small, report population normative data on a limited range of retinal vascular features, such as caliber, fractal dimension (FD), and vascular density.[10,11] This limits their usefulness for a comprehensive assessment of systemic health.

The current study addresses this gap by establishing a reference database of retinal vascular parameters derived from fundus photographs in a large population cohort, the UK Biobank.[12] Using the Retina-based Microvascular Health Assessment System (RMHAS),[13] a deep learning model, we report on the sex-stratified normative ranges of 114 arterial and venous measurements in the macula and peripheral retina for 5 geometric features of the retinal vascular network, including vascular caliber, complexity, density, branching angle (BA), and tortuosity.

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Methods

Study Design

We used deidentified data from the UK Biobank, a large population-based cohort study including participants aged 40 to 69 years. The study was launched in 2006 in the United Kingdom and introduced ocular examinations, including fundus photography, in 2009. The details of the study have been described elsewhere.[12]

Ethical Consideration

The current study utilized data from the UK Biobank, which obtained ethical approval from the North West Multi-centre Research Ethics Committee (reference number 06/MRE08/65). The UK Biobank study obtained consent from participants at enrollment. Our study adhered to the Declaration of Helsinki.

Inclusion and Exclusion Criteria

We included nonsmoking participants with a body mass index (BMI) of $\leq$30 (kg/m^2) who identified themselves as of White ethnicity. Those with a self-reported history of ocular disease, diabetes, cardiovascular or neurodegenerative disease, intraocular pressure (IOP) $\geq$21 mmHg, systolic blood pressure (SBP) $\geq$140 mmHg, or diastolic blood pressure $\geq$90 mmHg were excluded.[10,14] Table S1 (available at www.ophthalmologyscience.org) details definitions of variables used in the current study.

Retinal Vascular Network Analysis

The retinal fundus images were taken in a dark room without pupil dilation using the Topcon 3D OCT-1000 Mark II system.[15] The image quality was assessed using RMHAS, and those classified as "reject" were removed.[13] Subsequently, only 1 image with the best quality was kept for each participant. Retinal vascular parameters were obtained using RMHAS,[13] a deep learning algorithm for automated segmentation and quantification of retinal vascular networks. We extracted measurements of the following 5 retinal geometric features: caliber, density, tortuosity, BA, and complexity. Multiple measure types, namely the segmentation and quantification methods, were extracted for each retinal geometric feature (Fig 1). For measurements of parameters in micron units, we first obtained measurements in pixel units and then converted them to micron values to address the impact of magnification on the variance of measurements using the scale from the corresponding OCT.[16] Table S2 (available at www.ophthalmologyscience.org) provides definitions of those measure types. Building on that, measurements of arterial and venous vessels in the macula (6 mm $\times$ 6 mm area centered on the fovea) and peripheral (from the outer edge of the macula to the border) retina were further quantified.

Statistical Analysis

Continuous variables are presented as means (standard deviations [SDs]), and counts (percentages) were used for categorical variables. For RMHAS-generated retinal vascular measurements, outliers were removed using the Robustbase package, setting the range at 3 to account for skewness.[17] Multivariate imputation by chained equations was used to impute missing values.

The Kolmogorov–Smirnov test was performed to assess the normality of distributions. For comparison between men and women, when data for both groups followed a normal distribution, a t test was applied; otherwise, the Mann–Whitney U test was used. For comparison between age groups, when measurements were normally distributed, an analysis of variance was performed; otherwise, the Kruskal–Wallis H test was used. Violin plots were generated to show the distribution of retinal vascular measurements for men and women separately, further stratified by the decade of age, with intergroup differences labeled.

To explore changes in retinal vessel parameters (caliber, tortuosity, complexity, density, and BA) with age, SBP, BMI, glycated hemoglobin (HbA1c), and IOP, we constructed heatmaps depicting these associations. For correlation analyses, the Anderson–Darling test was used for the normality test. If variables were normally distributed, Pearson correlation coefficient was used; otherwise, Kendall rank correlation coefficient was calculated. To account for multiple comparisons, we applied the Bonferroni correction, adjusting the significance threshold accordingly. For significantly correlated variables after correction, we applied generalized additive models for location, scale, and shape separately for men and women to capture both linear and nonlinear associations. P-splines were utilized to smooth and enhance the localization of model fit.

We treated a 2-sided alpha $<$0.05 as significant for all statistical tests, with Bonferroni correction used for multiple comparisons. All analyses were performed using R, version 4.2.3 (The R Foundation for Statistical Computing). We followed STrengthening the Reporting of OBservational Studies in Epidemiology guidelines[18] (STROKE checklist, available at www.ophthalmologyscience.org).

Results

Characteristics of Participants

A total of 10 151 participants were included in the final analysis. Figure 2 details the participants included and excluded at each stage. The mean age was 53.0 years (SD 7.74). The overall sex distribution was 63.8% women and 36.2% men, with similar proportions observed across the age groups. Systolic blood pressure measurements showed an increasing trend with age, with means of 121, 123, and 126 mmHg in the 40 to 50, 50 to 60, and $>$60-year groups, respectively. Table 3 shows sample characteristics by decade age groups and for all participants.

Distribution of Retinal Vascular Measurements

Tables S4 and S5 (available at www.ophthalmologyscience.org) present the mean (SD) and the median (interquartile range) of retinal vascular measurements in the entire sample and by age group, and Table S6 (available at www.ophthalmologyscience.org) shows the mean (SD) of retinal vascular measurements for men and women separately with and without age stratification. Figures S3 to S7 (available at www.ophthalmologyscience.org) show the median (interquartile range) of retinal vascular measurements by sex and age group.

Caliber. The mean values of artery-to-vein ratio equivalent (AVRe), central retinal artery equivalent (CRAE), central retinal vein equivalent (CRVE), and width of arteries and veins were 0.653 (0.068), 152 (14.9) μm, 233 (21.5) μm, 56.6 (2.96) μm, and 63.3 (3.53) μm, respectively. The length-to-diameter ratio (LDR) was 12.8 (1.52) for arteries, 12.2 (1.06) for veins, and 13.6 (1.86) for vessels in the macular region (Table S4). Values of measurements for

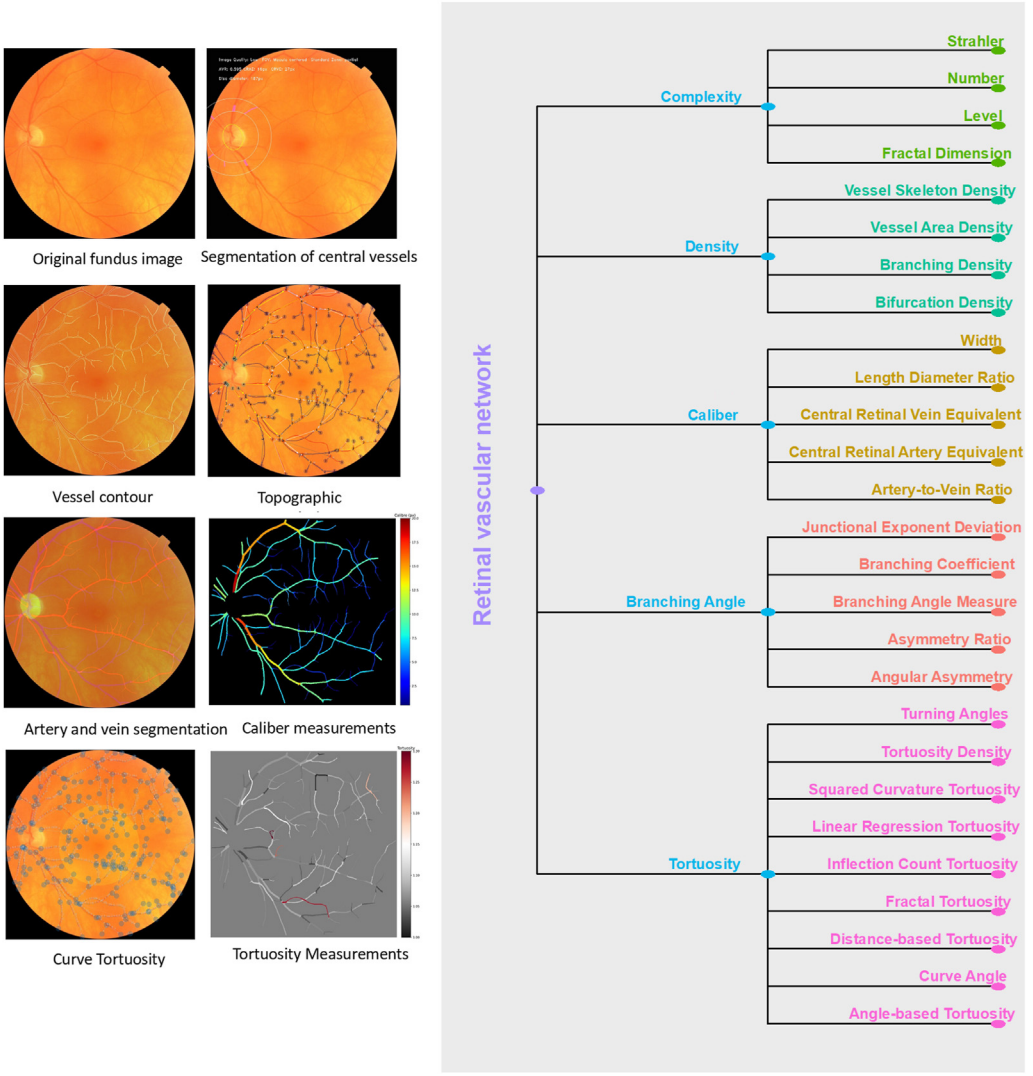

Figure 1. Retinal vascular network analysis. Notes: After retinal vascular network segmentation, we used 27 segmentation and quantification methods to extract measurements of the following 5 retinal vascular geometric features: caliber, density, tortuosity, branching angle, and complexity. Definitions can be found in Table S2.

women and men, stratified by age groups, can be found in Table S6.

Complexity. The mean value of FD, a quantitative, dimensionless measure for the complexity of the vascular network, was 1.77 (0.032), with arterial FD being 1.53 (0.039) and venular FD being 1.56 (0.025). The mean number of segments was 172 (45.2) and 174 (33.6) for arteries and veins, respectively, and 85.5 (22.0) in the macular region. The mean number of branching and bifurcation was 97.9 (28.5) and 51.8 (15.0), respectively, for arteries, and 100 (23.1) and 50.1 (11.3) for veins, respectively (Table S4).

Density. The mean vessel area density (VAD) of arteries and veins was 5.75% (0.915%) and 7.22% (0.735%), respectively, and the mean vessel skeleton density of arteries and veins was 1.45% (0.243%) and 1.57% (0.178%), respectively. The mean branching density and bifurcation density were 1.39% (0.172%) and 1.33% (0.204%), respectively, for arteries and 1.34% (0.142%) and 1.29% (0.159%), respectively, for veins. Chord length and arc length, which inversely reflect the bifurcation density of the vascular network (with longer lengths indicating less bifurcation and therefore lower network density), were 584 (82.3) and 634 (89.1), respectively, for arteries, and 596 (63.1) and 646 (68.9) for veins, respectively (Table S4).

BA. The mean angular asymmetry (AA) was 41.1° (3.736°) and 39.4° (3.434°) for arteries and veins, respectively, and the asymmetry ratio was 2.13 (0.334) and 2.49 (0.434), respectively. The mean BA was 47.1° (1.73°) and 46.7° (1.36°), respectively, for arteries and veins. The mean branching coefficient was 1.29 (0.092) and 1.22 (0.089) for arteries and veins, respectively (Table S4).

Tortuosity. The mean tortuosity density was 0.543 (0.037) and 0.590 (0.032) for arteries and veins,

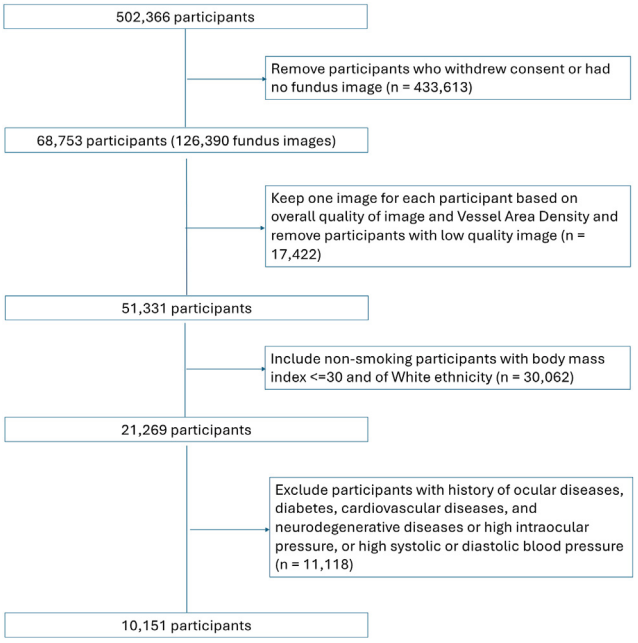

Figure 2. Participants' selection process. Notes: Out of 502 366 participants, 68 753 participants had fundus images. We first kept 1 image for each participant based on quality and then further removed those with poor-quality images. Among 51 331 participants with eligible images, we kept only nonsmoking participants of White ethnicity and further removed those with conditions that would affect retinal vessels.

respectively. The mean curve angle (CA) and fractal tortuosity (FT) were 9.71° (1.49°) and 0.84 (0.009), respectively, for arteries and 10.1° (0.992°) and 0.838 (0.008), respectively, for veins. In addition, inflection count tortuosity and distance-based tortuosity were 0.226 (0.017) and 1.09 (0.009), respectively, for arteries and 0.245 (0.016) and 1.08 (0.005), respectively, for veins (Table S4).

Associations of Retinal Vascular Measurements with Health Metrics

Figure 8 presents correlations between retinal vascular measurements and health metrics, including age, SBP, IOP, HbA1c, and BMI with *P* value adjusted for Bonferroni correction. Coefficients and adjusted *P* values can be found in Table S7 (available at www.ophthalmologyscience.org). Across all health metrics included in the analysis, age and SBP were significantly associated with most retinal vascular measurements with the highest coefficients. Figure 9 shows the associations of selected retinal vascular measurements with age and SBP assessed with generalized additive models for location, scale, and shape with P-splines, accounting for the effect of remaining health metrics. Figures S10 to S12 (available at www.ophthalmologyscience.org) further present correlation among retinal parameters in a healthy population, distribution of retinal parameters in a population with systemic conditions, and the correlation between retinal parameters and refractive error. The association assessed using original values can be found in Figure S13 (available at www.ophthalmologyscience.org).

Caliber. Age was associated with all caliber measurements. Systolic blood pressure showed an association with all arterial measurements as well as measurements in the macular region. Among venular measurements, SBP showed an association with the venular LDR only. The BMI also showed associations with all arterial measurements, as well as AVRe and LDR in the macular region. Intraocular pressure showed an association only with the width of veins and AVRe, and HbA1c was associated with both arterial and venular LDRs, as well as the width of veins.

Complexity. Intraocular pressure was not associated with any complexity measurements, while age was associated with all except the number of venular trees and the number of trees in the macular region. Systolic blood pressure and HbA1c were associated with all measurements of number of bifurcation, number of branching, number of segments, and FD. The BMI was associated with the arterial FD, number of arterial branching, bifurcation, segments, and number of branching and segments in the macular region.

Density. All density measurements showed a strong association with age, SBP, and HbA1c. Intraocular pressure was only associated with VAD of veins outside the macular region. The BMI was associated with all arterial density measurements and none of the venular measurements or measurements in the macular region.

BA. Age was associated with all venular measurements, except for the venular BA at the edge. In addition, age was associated with arterial AA, BA, and AA and BA at the edge. For measurements in the macular region, age showed an association with only BA. Systolic blood pressure was associated with arterial AA, junctional exponent deviation, BA, and BA at the edge, as well as junctional exponent deviation in the macular region. Intraocular pressure and HbA1c did not show an association with any of the BA measurements, and the BMI was only associated with BA at the edge in the macular region.

Tortuosity. Age was associated with arterial and venular inflection count tortuosity, FT, and CA, as well as venular squared curvature tortuosity and arterial distance-based tortuosity. Systolic blood pressure was associated with arterial CA and FT. Intraocular pressure was not associated with any of the tortuosity measurements, BMI with none but arterial CA and distance-based tortuosity, and HbA1c with none but arterial and venular FT.

Discussion

The current study selected 10 000 healthy participants from a large database to establish normative ranges for a wide variety of retinal vascular parameters. Ours is the first study to present a comprehensive suite of age- and sex-stratified retinal vascular measurements, categorized into 5 distinct groups and providing separate parameters for veins and arteries and locations within and outside the macular region. This analysis provides a foundation for future research exploring the clinical significance of variations in retinal vasculature parameters in disease diagnosis and risk

Table 3. Baseline Characteristics of Participants

Characteristics	Overall n = 10 151	40 to 50 Years n = 3888	50 to 60 Years n = 3803	>60 Years n = 2460
Age, yrs	53.0 (7.74)	45.0 (2.73)	54.3 (2.86)	63.5 (2.75)
Sex				
Female, N (%)	6476 (63.8%)	2444 (62.9%)	2455 (64.6%)	1577 (64.1%)
Male, N (%)	3675 (36.2%)	1444 (37.1%)	1348 (35.4%)	883 (35.9%)
Body mass index (kg/m^2)				
Mean (SD)	24.5 (2.73)	24.5 (2.77)	24.5 (2.75)	24.5 (2.66)
Missing, N (%)	31 (0.31%)	13 (0.33%)	10 (0.26%)	8 (0.33%)
Diastolic blood pressure (mmHg)				
Mean (SD)	75.2 (7.07)	75.3 (7.10)	75.5 (7.10)	74.6 (6.93)
Missing, N (%)	32 (0.32%)	11 (0.28%)	12 (0.32%)	9 (0.37%)
Systolic blood pressure (mmHg)				
Mean (SD)	123 (10.1)	121 (10.2)	123 (9.91)	126 (9.30)
Missing, N (%)	32 (0.32%)	11 (0.28%)	12 (0.32%)	9 (0.37%)
High-density lipoprotein (mmol/l)				
Mean (SD)	1.58 (0.379)	1.52 (0.348)	1.62 (0.398)	1.61 (0.386)
Missing, N (%)	1414 (13.9%)	511 (13.1%)	569 (15.0%)	334 (13.6%)
Low-density lipoprotein (mmol/l)				
Mean (SD)	3.54 (0.789)	3.31 (0.729)	3.63 (0.780)	3.77 (0.797)
Missing, N (%)	889 (8.75%)	319 (8.21%)	351 (9.23%)	219 (8.90%)
Cholesterol (mmol/l)				
Mean (SD)	5.73 (1.03)	5.38 (0.932)	5.87 (1.01)	6.05 (1.04)
Missing, N (%)	871 (8.58%)	315 (8.10%)	347 (9.12%)	209 (8.50%)
Intraocular pressure (mmHg)				
Mean (SD)	14.7 (2.96)	14.5 (2.96)	14.7 (3.01)	15.0 (2.88)
Missing, N (%)	267 (2.63%)	103 (2.65%)	101 (2.66%)	63 (2.56%)
Glycated hemoglobin (mmol/mol)				
Mean (SD)	33.9 (3.59)	32.7 (3.23)	34.2 (3.18)	35.3 (4.14)
Missing, N (%)	1220 (12.0%)	402 (10.3%)	493 (13.0%)	325 (13.2%)

N = number; SD = standard deviation.
Categorical variables are presented as counts (percentages), while continuous variables are presented as means (SDs).

assessment. As more retinal vascular measurements are increasingly identified as biomarkers for systemic conditions, the normative ranges established in our study become more useful.

In our study, the mean values of CRAE, CRVE, and AVRe, 152 (14.9) µm, 233 (21.5) µm, and 0.653 (0.068), respectively, were similar to those reported in the Australian population (152 [14.0] µm, 221 [19.0] µm, and 0.69 [0.06]).[19] However, measurements in prior studies have ranged from 163 to 192 µm for CRAE and 210 to 250 µm for CRVE.[10,20,21] While studies differed in age and inclusion criteria, the most important reason for discrepancies may lie in varying measurement approaches. The arterial and venular FD values in the current report were 1.53 (0.04) and 1.56 (0.03), respectively, in women and 1.53 (0.04) and 1.57 (0.03), respectively, in men, which were somewhat higher than those reported in another recent study.[22] As prior reports show, FD is negatively associated with cardiovascular disease and mortality risk;[8,23] a higher FD in our study may reflect our strict inclusion criteria, excluding all participants with cardiovascular disease risk factors.

Among all the health metrics we examined, age had the strongest association with retinal vessel measurements. Central retinal artery equivalent, CRVE, and AVRe all decreased with age, consistent with data reported for another healthy cohort.[24] In contrast, LDRs of all veins and arteries, as well as those in the macular region, were all positively associated with age, consistent with a previous study reporting a positive and independent association between a higher arteriolar LDR and older age.[25] In addition, age showed a strong negative association with all density measurements and most complexity measurements, consistent with previous studies reporting sparser vascular networks and less complex microvasculature with increasing age.[26–28] Specifically, in our study, the correlation matrix revealed correlations of −0.24 and −0.21 for age with arterial FD and VAD, respectively, showing trends consistent with findings from a previous study (−0.17 and −0.25).[22]

Systolic blood pressure was associated with reduced CRAE and CRVE, with a greater reduction in CRAE and, consequently, a reduced AVRe. The same trend was found previously in children as well, indicating such trends start

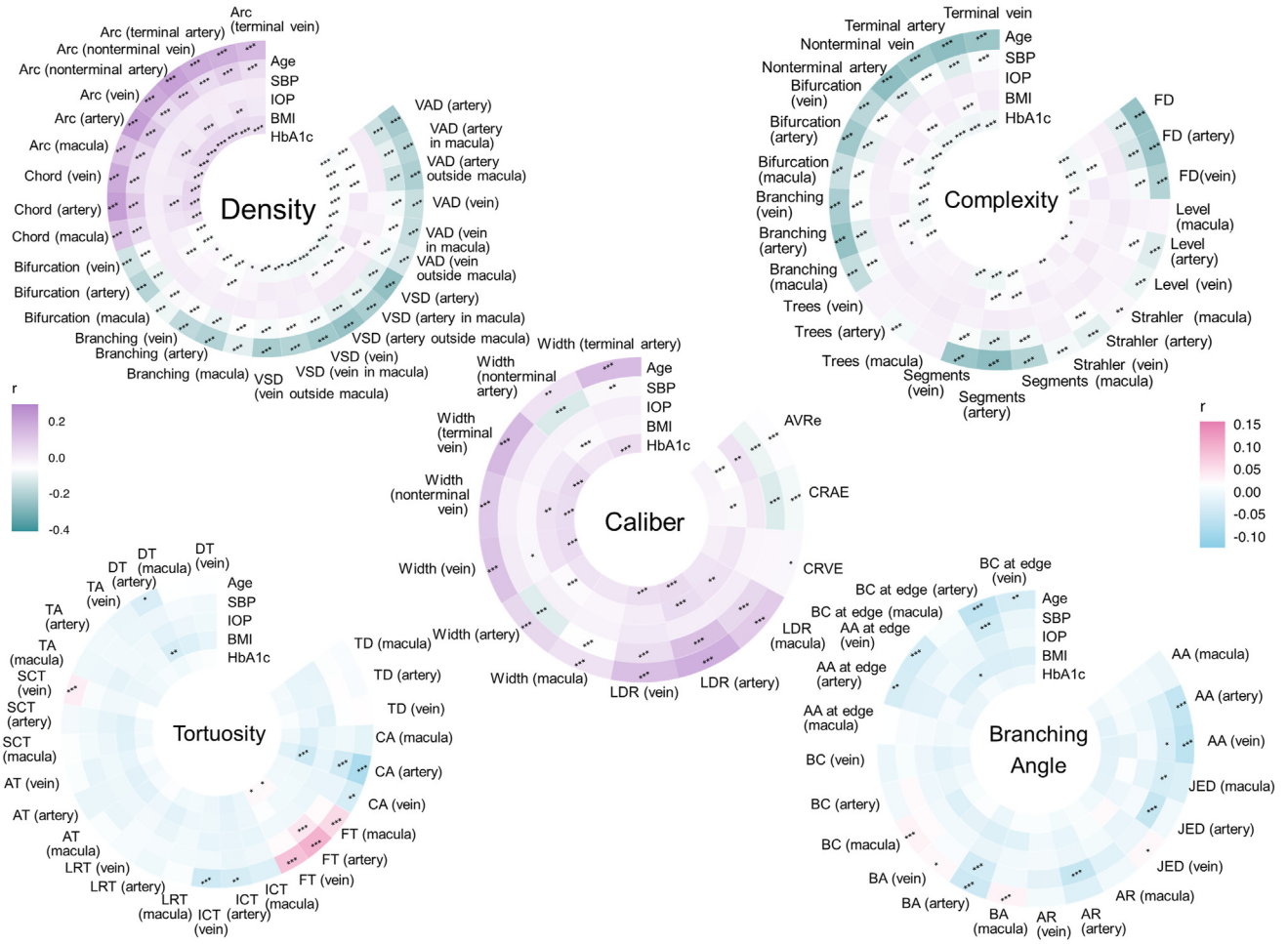

Figure 8. Correlations between retinal vascular measurements and age, SBP, IOP, HbA1c, and BMI. The *P* value was adjusted with Bonferroni correction. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$. AA = angular asymmetry; AR = asymmetry ratio; AT = angle-based tortuosity; BC = branching coefficient; BMI = body mass index; CA = curve angle; CRAE = central retinal artery equivalent; CRVE = central retinal vein equivalent; DT = distance-based tortuosity; FT = fractal tortuosity; HbA1c = glycated hemoglobin; ICT = inflection count tortuosity; IOP = intraocular pressure; JED = junctional exponent deviation; LDR = length-to-diameter ratio; LRT = linear regression tortuosity; SBP = systolic blood pressure; SCT = squared curvature tortuosity; TA = turning angles; TD = tortuosity density; VAD = vessel area density; VSD = vessel skeleton density.

early in life.[29,30] As with age, SBP was also associated with all LDR measurements. A previous study also revealed a positive association of SBP with arteriolar LDR,[25] while they reported no association for venular LDR. Systolic blood pressure exhibited a negative association with both complexity and density measurements for both arteries and veins, within and outside the macular region. A similar inverse association has also been reported,[26,28] including in a multiethnic population study.[31] As shown in Figure 9, the associations of retinal vascular measurements with age and SBP were generally linear. Since we adopted strict inclusion criteria to include only participants without cardiovascular disease risk factors, caution is warranted when interpreting these results.

Glycated hemoglobin was also associated with retinal vascular measurements. However, the association was mainly found for complexity and density measurements, both negative. An increase in HbA1c could affect endothelial function and vascular bifurcation,[32–34] thereby leading to lower complexity and density of the retinal network. The association with BMI was mainly found for caliber measurements, which were positively associated with CRVE and width of veins and negatively associated with CRAE, AVRe, and width of arteries, consistent with previous studies.[29,35] We also showed that, after excluding those with ocular conditions that could affect the retinal vascular network, including high IOP, glaucoma, and retinal diseases, in participants with relatively healthy retinal vascular networks, no association with IOP was found for most retinal geometric measurements. We found IOP was negatively associated with both CRVE and the width of veins, which may also explain its positive association with AVRe and venular VAD (across the fundus and outside the macular region). Most studies in glaucoma patients have also identified a reduction in venular caliber.[36]

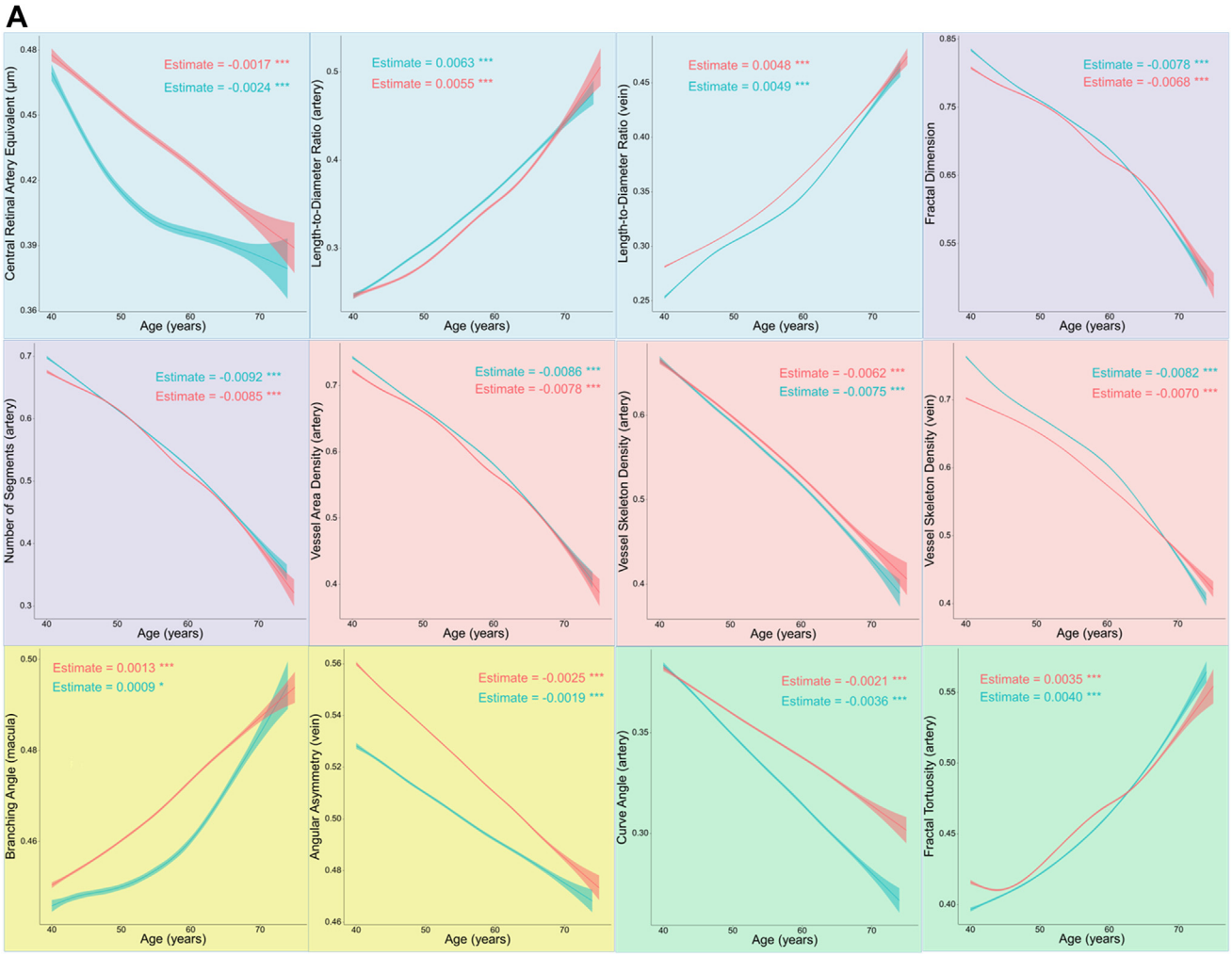

Figure 9. Associations of selected retinal vascular measurements with (**A**) age and (**B**) systolic blood pressure (SBP) for men (n = 3675) and women (n = 6476). Generalized additive models for location, scale, and shape were fitted for men and women separately with P-splines. The y-axis shows the partial effect of age and SBP on retinal vascular measurements, accounting for the impact of other health metrics. The retinal vascular measurements were rescaled to the 0 to 1 range to improve the comparability (the association assessed using original values can be found in Fig S13, available at www.ophthalmologyscience.org).

Our study has several strengths. First, we reported normative data stratified by sex and age. This provides a valuable reference database for age- and sex-specific studies exploring retinal vascular damage. Second, separate measurements of arteries and veins allow researchers to precisely investigate diseases that primarily affect one or the other. Third, we reported >100 measurements. This provides a large set of candidates for potential biomarker identification and assessment of retinal vascular alteration. In addition, we found the changes in arterial measurements with age and SBP were more prevalent and significant than those in venular measurements. This suggests that arterial measurements may serve as more sensitive biomarkers for age- and blood pressure–related systemic conditions and are of value for further exploration.

We also recognize limitations in our research. First, our analysis was based on UK Biobank participants of White ethnicity. It would be important to carry out a similar study among non-White populations of similar sample sizes to understand the differences among different ethnicities. Consequently, there is a need for future studies to establish normative ranges within multiethnic populations. Additionally, due to the strict inclusion criteria necessary for reporting normative ranges, we found that associations with other health metrics were generally linear. Therefore, caution is advised when interpreting these results beyond the normal range. Lastly, our study did not compare vessel parameters with those generated by alternative software, which may limit the generalizability of our findings to analyses conducted with different analytic algorithms. This limitation arises in part from the inability of other software to produce as extensive a set of parameters. Nonetheless, the algorithm we used is validated,[7,8,37,38] and the associations we identified are consistent with

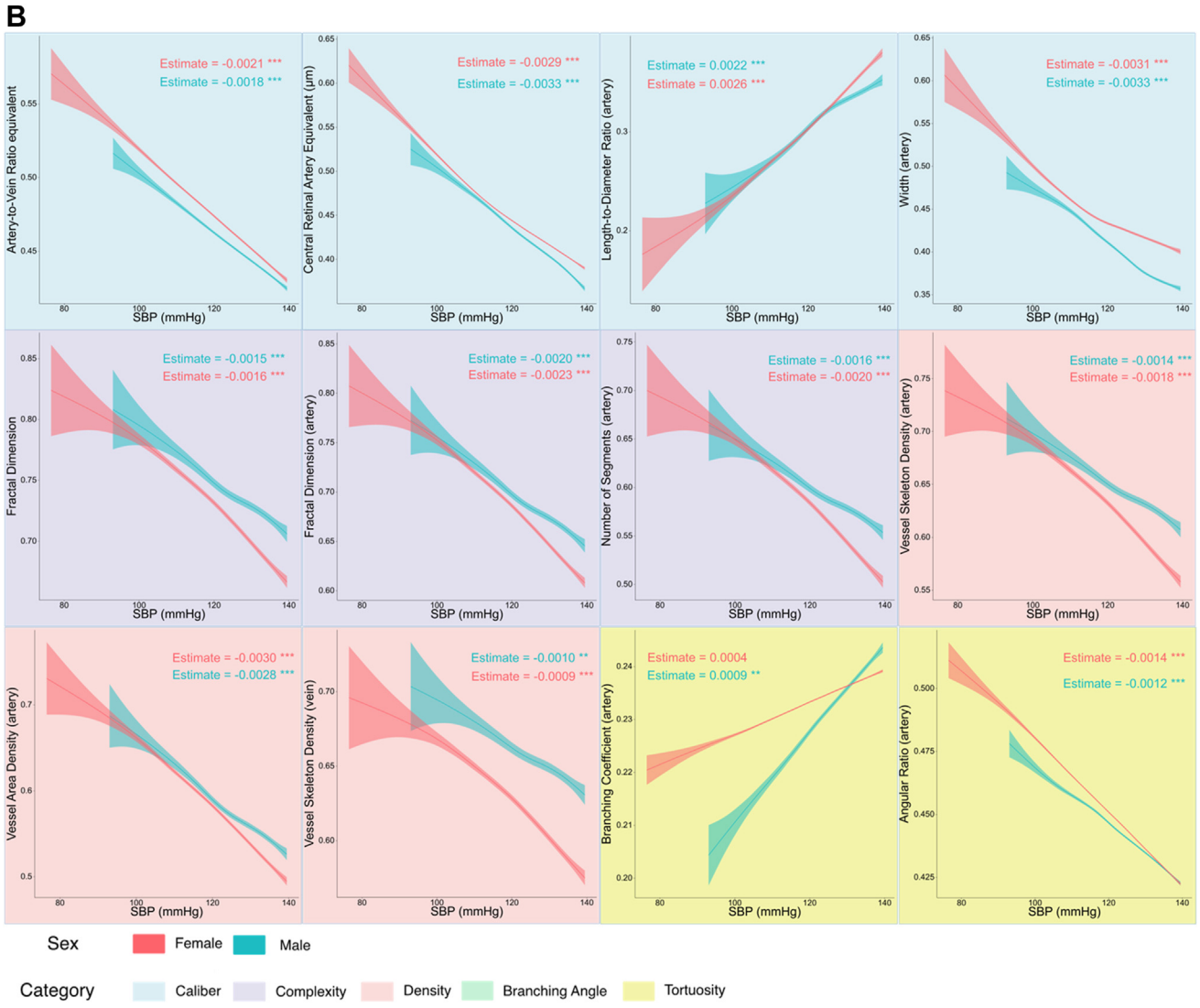

Figure 9. Continued.

those reported in previous studies. Future research is required to provide a more comprehensive perspective on this issue.

With artificial intelligence facilitating segmentation and quantification of the retinal vascular network, increasing evidence validates the associations of retinal vascular biomarkers with systemic conditions and mortality risk, underscoring their potential as a low-cost, noninvasive, easy-to-use, and widely available screening tool. By reporting population normative data for a comprehensive set of retinal vascular measurements, our study enables a better understanding of the severity of alterations in the retinal vascular network. This offers a quantifiable approach to the use of retinal vascular biomarkers as an assessment and diagnostic tool.

Availability of Data and Material

This study used data from a public, open-access repository, the UK Biobank study (https://www.ukbiobank.ac.uk/).

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Footnotes and Disclosures

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HUMAN SUBJECTS: Human subjects were included in this study. The current study utilized data from the UK Biobank, which obtained ethical approval from the North West Multi-Centre Research Ethics Committee (reference number 06/MRE08/65). The UK Biobank study obtained consent from participants at enrollment. Our study adhered to the Declaration of Helsinki.

No animal subjects were used in this study.

Author Contributions:

Conception and design: Vingrys, Shang, Zhang, Shi, Congdon, He

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Abbreviations and Acronyms:
AA = angular asymmetry; **AVRe** = artery-to-vein ratio equivalent; **BA** = branching angle; **BMI** = body mass index; **CA** = curve angle; **CRAE** = central retinal artery equivalent; **CRVE** = central retinal vein equivalent; **FD** = fractal dimension; **FT** = fractal tortuosity; **HbA1c** = glycated hemoglobin; **IOP** = intraocular pressure; **LDR** = length-to-diameter ratio; **RMHAS** = Retina-based Microvascular Health Assessment System; **SBP** = systolic blood pressure; **SD** = standard deviation; **VAD** = vessel area density.

Keywords:
Retinal vascular measurements, Retina-based Microvascular Health Assessment System, UK Biobank, Normative population data.

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