Research Square

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Carotid functional abnormalities without detectable intima– media thickening in adults with high-normal blood pressure: a retrospective cross-sectional quantitative ultrasound study

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Research Article

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Abstract

Background

We investigated whether quantitative arterial stiffness (QAS)-derived functional abnormalities could be detected in adults with high-normal blood pressure without a corresponding increase in quantitative intima–media thickness (QIMT) after covariate adjustment.

Methods

This retrospective cross-sectional study included adults assessed at Dongzhimen Hospital, Beijing, between November 2021 and December 2022. Four blood pressure groups were defined. Outcomes were maximum QIMT, pulse wave velocity (PWV), distensibility coefficient (DC), compliance coefficient (CC), and a carotid functional stiffness score (CFSS). Models adjusted for age, sex, and body mass index; functional models were further QIMT-adjusted.

Results

Among 312 participants, 114 had ideal and 91 had high-normal blood pressure. Compared with ideal blood pressure, high-normal blood pressure was not associated with maximum QIMT (standardized adjusted difference, − 0.04; 95% confidence interval [CI], − 0.25 to 0.17; false-discovery-rate-adjusted P = 0.761), but was associated with higher PWV (0.38; 95% CI, 0.21 to 0.56), lower DC (− 0.45; 95% CI, − 0.63 to − 0.27), lower CC (− 0.42; 95% CI, − 0.67 to − 0.17), and higher CFSS (0.43; 95% CI, 0.23 to 0.63). All remained significant after multiple-testing correction and QIMT adjustment. Isolated functional impairment was more frequent with high-normal than ideal blood pressure (37.8% vs 15.2%; adjusted odds ratio, 2.61; 95% CI, 1.27 to 5.36).

Conclusions

High-normal blood pressure was associated with QAS-derived functional abnormalities without a corresponding increase in QIMT after covariate adjustment. These findings support complementary carotid assessment but do not establish temporal sequence or prognosis.

Background

Blood pressure below the conventional diagnostic threshold for hypertension may still be associated with cardiovascular risk. Depending on the guideline system, high-normal blood pressure and related prehypertensive phenotypes represent transitional states in which vascular alterations may emerge before sustained hypertension becomes clinically established. Previous studies have reported subclinical carotid damage [1] and greater local carotid stiffness [2] in individuals with prehypertension

than in normotensive individuals. Central blood pressure and carotid intima–media thickness have also been associated with incident hypertension among people with high-normal blood pressure [3].

Carotid intima–media thickness characterizes arterial wall structure, whereas pulse wave velocity (PWV), distensibility coefficient (DC), and compliance coefficient (CC) assess local arterial function [4, 5]. These domains are related but provide distinct information. Functional measures may respond to pressure loading, vascular tone, and elastic reserve without a concurrently detectable difference in wall thickness. Comparing structural and functional measures in the same participants may therefore reveal a vascular phenotype that QIMT alone does not capture.

We therefore investigated whether adults with high-normal blood pressure had QAS-derived carotid functional abnormalities without a corresponding increase in maximum QIMT after covariate adjustment. We hypothesized that high-normal blood pressure would be associated with higher PWV and lower DC or CC even when QIMT was not independently increased. We also constructed a composite carotid functional stiffness score (CFSS) and explored an isolated functional-impairment phenotype. Because the study was cross-sectional, the intended inference was concurrent structure–function discordance rather than a temporal sequence.

Methods

Study design and participants

This single-center retrospective cross-sectional study used clinical carotid ultrasound data from the Department of Neurology, Dongzhimen Hospital, Beijing University of Chinese Medicine. The source population comprised adults who underwent QIMT and QAS assessment between November 2021 and December 2022. The study is reported in accordance with the STROBE statement [9]. The Ethics Committee of Dongzhimen Hospital approved the study (2022DZMEC-338) and waived the requirement for informed consent because the analysis used retrospectively collected clinical data.

The original workbook contained 355 records, and the age-restricted worksheet contained 336 examinations. Adults aged 18–74 years with available QIMT and QAS data were eligible. A standardized internal key derived from name and sex was used solely to identify repeated examinations; identifiers were not retained in submitted outputs. For participants with repeated examinations, the first eligible examination was retained for the primary analysis, yielding 312 unique participants. All eligible examinations from the prespecified period were considered, and no a priori sample-size calculation was performed. Repeated examinations were used only in sensitivity analyses.

Blood pressure measurement and classification

After 30 min of seated rest, blood pressure was measured using a fully automated medical electronic monitor (HBP-9030; Omron Healthcare, Kyoto, Japan). An appropriately sized arm cuff was positioned

according to guideline recommendations. Three readings were obtained at 5-min intervals, and the arithmetic mean of all three readings was used for classification and QAS calculations.

Participants were classified into four groups according to documented hypertension history and mean clinic blood pressure, in alignment with Chinese guideline categories [11]. Ideal blood pressure was defined as no previous hypertension, systolic blood pressure <120 mmHg, and diastolic blood pressure <80 mmHg. High-normal blood pressure was defined as no previous hypertension and systolic blood pressure 120–139 mmHg and/or diastolic blood pressure 80–89 mmHg. Previous hypertension was defined as a documented diagnosis or history, regardless of the index clinic value. Elevated office blood pressure was defined as no previous hypertension and systolic blood pressure ≥140 mmHg and/or diastolic blood pressure ≥90 mmHg. Because repeated-visit or ambulatory confirmation was unavailable, the latter group was not labelled newly diagnosed hypertension.

Carotid ultrasound assessment

A single qualified departmental sonographer performed all examinations using an Esaote MyLab 90 color Doppler system with an LA 523 vascular transducer (4–15 MHz) and built-in QIMT/QAS analysis software. The institutional acquisition protocol reported by Wang et al. was followed [10]. Participants were examined supine without a pillow, with the head neutral or slightly rotated away from the examined side. In QIMT mode, the reference line was positioned at the origin of the carotid bulb and the sampling box was placed 1 cm proximal to it. The software measured intima–media thickness over six cardiac cycles when the measurement standard deviation was ≤20 μm. In QAS mode, the software derived DC, CC, alpha, beta, and PWV from blood pressure, arterial diameter and area, measurement distance, and pulse-transit time.

Right and left QIMT values were converted from micrometers to millimeters; the maximum available value was the primary structural outcome. Bilateral functional parameters were averaged when both sides were available; otherwise, the available side was used according to the prespecified script. The archived records did not retain the exact embedded software version or formal intra-observer repeatability metrics.

Outcomes and covariates

Maximum QIMT was the primary structural outcome, and mean carotid PWV was the primary functional outcome. Mean DC and CC were prespecified key secondary functional outcomes. Robustly processed standardized values were combined as CFSS = zPWV − zDC − zCC and re-standardized, with higher values indicating greater functional stiffness. CFSS and the derived phenotypes were exploratory. Age, sex, and body mass index were prespecified covariates. Smoking, diabetes, dyslipidemia, antihypertensive treatment, carotid plaque, renal function, menopausal status, and laboratory data were unavailable or insufficiently complete and therefore could not be included.

Statistical analysis

Continuous variables are presented as mean ± standard deviation or median [interquartile range], as appropriate; categorical variables are presented as n (%). Groups were compared using analysis of variance, Kruskal–Wallis tests, or chi-square tests, as appropriate. Separate multivariable linear regression models were fitted for each carotid outcome, with blood pressure group as the exposure and ideal blood pressure as the reference. Models were adjusted for age, sex, and body mass index.

QIMT was winsorized at the 1st and 99th percentiles and standardized. Skewed PWV, DC, and CC measures were log-transformed where appropriate, winsorized, and standardized. Heteroscedasticity-consistent standard errors were used. The Benjamini–Hochberg false discovery rate (FDR) procedure addressed multiple comparisons. To assess whether functional associations were explained by measurable structural thickening, functional models were further adjusted for maximum QIMT. Trend analyses treated blood pressure group as an ordinal variable.

Exploratory structural and functional abnormalities were defined as maximum QIMT and CFSS, respectively, above the 75th percentile of the ideal-blood-pressure group. Isolated functional impairment was defined as functional abnormality without structural abnormality. Logistic regression was adjusted for age, sex, and body mass index. Within the ideal and high-normal groups, an exploratory discrimination analysis compared a model containing age, sex, body mass index, and QIMT with the same model plus CFSS. Complete cases were analyzed without imputation, and model denominators are reported. Sensitivity analyses included original-scale and winsorized outcomes, repeated-examination mixed models, bilateral agreement, and correlation analyses. Analyses and figures were produced using R 4.5.1.

Results

Participants

The primary analysis included 312 unique participants: 114 with ideal blood pressure, 91 with high-normal blood pressure, 75 with previous hypertension, and 32 with elevated office blood pressure (Fig. 1). The mean age was 40.7 ± 15.0 years, and 115 participants (36.9%) were male. Age, sex distribution, body mass index, and clinic blood pressure differed across groups (Table 1). Body mass index was missing for two participants, maximum QIMT for one, and CFSS components for another. Consequently, outcome-specific primary models included 309 participants, whereas the joint structure–function phenotype analysis included 308 (Additional file 1, Supplementary Tables 7 and 9).

Table 1 Baseline characteristics by blood pressure group

Characteristic	Overall	Ideal BP	High-normal BP	Previous hypertension	Office-elevated BP	P value
Age, years	40.7 ± 15.0	32.9 ± 11.3	40.4 ± 15.1	51.8 ± 11.5	43.2 ± 17.3	<0.001
Male sex, n (%)	115 (36.9%)	21 (18.4%)	46 (50.5%)	34 (45.3%)	14 (43.8%)	<0.001
Body mass index, kg/m²	23.6 ± 3.6	21.4 ± 2.8	23.6 ± 3.2	25.7 ± 3.2	26.1 ± 3.8	<0.001
Systolic blood pressure, mmHg	125.3 ± 18.4	107.6 ± 7.4	125.7 ± 5.8	143.5 ± 15.4	144.9 ± 13.9	<0.001
Diastolic blood pressure, mmHg	76.9 ± 11.8	66.8 ± 6.4	77.9 ± 6.7	87.6 ± 11.2	84.7 ± 9.3	<0.001
Maximum QIMT, mm	0.663 ± 0.128	0.600 ± 0.095	0.638 ± 0.106	0.762 ± 0.128	0.723 ± 0.125	<0.001
Mean PWV, m/s	6.9 ± 1.8	5.7 ± 1.2	6.9 ± 1.5	8.1 ± 1.5	8.0 ± 2.5	<0.001
Mean β, dimensionless	7.43 [5.57, 10.16]	6.14 [4.85, 7.79]	8.15 [5.57, 10.61]	9.83 [7.52, 12.29]	7.97 [6.40, 14.13]	<0.001
Mean DC, 1/kPa	0.02 [0.01, 0.03]	0.03 [0.03, 0.04]	0.02 [0.01, 0.03]	0.01 [0.01, 0.02]	0.02 [0.01, 0.02]	<0.001
Mean CC, mm²/kPa	0.94 [0.71, 1.19]	1.15 [0.92, 1.44]	0.91 [0.71, 1.12]	0.77 [0.58, 0.95]	0.87 [0.57, 0.96]	<0.001

Values are mean ± standard deviation, median [interquartile range], or n (%). BP, blood pressure; CC, compliance coefficient; DC, distensibility coefficient; PWV, pulse wave velocity; QIMT, quantitative intima–media thickness.

Carotid structure and function by blood pressure status

After adjustment for age, sex, and body mass index, maximum QIMT did not differ between the high-normal and ideal blood pressure groups (standardized adjusted difference, −0.04; 95% CI, −0.25 to 0.17; P=0.729; FDR-adjusted P=0.761). By contrast, high-normal blood pressure was associated with higher mean PWV (0.38; 95% CI, 0.21 to 0.56), lower mean DC (−0.45; 95% CI, −0.63 to −0.27), lower mean CC (−0.42; 95% CI, −0.67 to −0.17), and higher CFSS (0.43; 95% CI, 0.23 to 0.63). The corresponding FDR-adjusted P values were <0.001, <0.001, 0.002, and <0.001, respectively (Fig. 2; Table 2).

Table 2 Adjusted associations with carotid outcomes

Outcome	Comparison	Beta (95% CI)	P value	FDR-adjusted P value	N
Maximum QIMT	High-normal BP vs ideal BP	−0.04 (−0.25, 0.17)	0.729	0.761	309
Maximum QIMT	Previous hypertension vs ideal BP	0.50 (0.21, 0.78)	<0.001	0.001	309
Maximum QIMT	Office-elevated BP vs ideal BP	0.50 (0.15, 0.84)	0.005	0.008	309
Mean PWV	High-normal BP vs ideal BP	0.38 (0.21, 0.56)	<0.001	<0.001	309
Mean PWV	Previous hypertension vs ideal BP	0.46 (0.21, 0.70)	<0.001	<0.001	309
Mean PWV	Office-elevated BP vs ideal BP	0.59 (0.28, 0.90)	<0.001	<0.001	309
Mean DC	High-normal BP vs ideal BP	−0.45 (−0.63, −0.27)	<0.001	<0.001	309
Mean DC	Previous hypertension vs ideal BP	−0.66 (−0.90, −0.41)	<0.001	<0.001	309
Mean DC	Office-elevated BP vs ideal BP	−0.72 (−1.02, −0.41)	<0.001	<0.001	309
Mean CC	High-normal BP vs ideal BP	−0.42 (−0.67, −0.17)	0.001	0.002	309
Mean CC	Previous hypertension vs ideal BP	−0.32 (−0.67, 0.03)	0.077	0.109	309
Mean CC	Office-elevated BP vs ideal BP	−0.62 (−1.00, −0.24)	0.001	0.002	309
CFSS	High-normal BP vs ideal BP	0.43 (0.23, 0.63)	<0.001	<0.001	309
CFSS	Previous hypertension vs ideal BP	0.49 (0.22, 0.77)	<0.001	<0.001	309
CFSS	Office-elevated BP vs ideal BP	0.66 (0.34, 0.99)	<0.001	<0.001	309

Beta values are standardized adjusted differences from ideal blood pressure. Models adjusted for age, sex, and body mass index. CFSS, carotid functional stiffness score; CI, confidence interval; FDR, false discovery rate.

Participants with previous hypertension or elevated office blood pressure showed a broader pattern of carotid abnormalities. Maximum QIMT was higher in both groups than in the ideal blood pressure group (standardized difference, 0.50 for each; FDR-adjusted P=0.001 and 0.008, respectively), while PWV and DC were also abnormal in both groups (Table 2).

Structure-adjusted and exploratory analyses

Further adjustment for maximum QIMT did not materially alter the associations of high-normal blood pressure with PWV (0.38; 95% CI, 0.21 to 0.56), DC (−0.45; 95% CI, −0.63 to −0.27), CC (−0.41; 95% CI, −0.66 to −0.16), or CFSS (0.43; 95% CI, 0.23 to 0.63); all remained significant after FDR correction (Additional file 1, Supplementary Tables 3–4). Functional measures worsened progressively across ordered blood pressure categories, with CFSS increasing by 0.22 SD per category (95% CI, 0.12 to 0.32; FDR-adjusted P<0.001; Supplementary Table 5).

The phenotype analysis included 112 participants with ideal blood pressure, 90 with high-normal blood pressure, 74 with previous hypertension, and 32 with elevated office blood pressure. Isolated functional impairment was observed in 34 of 90 participants with high-normal blood pressure (37.8%) and 17 of 112 participants with ideal blood pressure (15.2%). After adjustment for age, sex, and body mass index, the odds ratio was 2.61 (95% CI, 1.27 to 5.36; P=0.009; Supplementary Tables 6–7 and Supplementary Fig. 3). Adding CFSS to a model containing age, sex, body mass index, and QIMT increased the area under the curve for cross-sectional discrimination of high-normal from ideal blood pressure from 0.752 to 0.795 (likelihood-ratio P<0.001; Supplementary Table 8).

Maximum QIMT increased with age (Fig. 3). After adjustment for sex, body mass index, systolic blood pressure, and diastolic blood pressure, each 10-year increase in age was associated with a 0.041-mm higher QIMT (95% CI, 0.033 to 0.049; P<0.001). Correlation, bilateral-agreement, original-scale, and repeated-examination analyses supported the overall direction of the primary findings (Additional files 1–2).

Discussion

Adults with high-normal blood pressure had QAS-derived carotid functional abnormalities without an independently detectable increase in maximum QIMT. Higher PWV, lower DC and CC, and higher CFSS persisted after further adjustment for QIMT. The isolated functional-impairment phenotype was also more frequent in the high-normal blood pressure group. The central finding is therefore concurrent structure–function discordance: functional abnormalities were detectable in a group with no adjusted difference in QIMT. Because the study was cross-sectional, these results do not show that functional change preceded structural change.

These findings are consistent with evidence that prehypertensive blood pressure is associated with subclinical carotid damage [1] and increased local carotid stiffness [2]. Our study extends this literature by comparing QIMT with multiple QAS-derived functional measures within the same cohort. The null adjusted QIMT comparison is part of this contrast and should not be interpreted as evidence that the carotid artery is unaffected. Functional parameters respond to wall tension, vascular tone, smooth-muscle behavior, and elastic reserve, whereas QIMT reflects wall structure [4, 5]. Modestly elevated

blood pressure may therefore alter elastic behavior without producing a concurrently measurable difference in wall thickness. This explanation is biologically plausible but remains inferential.

From a clinical perspective, a non-elevated QIMT does not necessarily indicate normal carotid function. QAS may provide complementary information in adults whose blood pressure is above ideal but below the clinic threshold for hypertension. However, CFSS and the isolated functional-impairment phenotype were based on internal thresholds and should not be interpreted as diagnostic tools. Moreover, the incremental-discrimination analysis was cross-sectional and does not demonstrate prediction of incident hypertension or cardiovascular events.

Strengths include measurement of QIMT and QAS-derived functional parameters in the same participants, subject-level de-duplication, prespecified structural and functional endpoints, covariate adjustment, FDR correction, and sensitivity analyses. Several limitations should also be acknowledged. This was a single-center retrospective study with a moderate sample and a relatively small elevated-office-blood-pressure group. Important confounders—including smoking, diabetes, dyslipidemia, antihypertensive therapy, carotid plaque, renal function, and menopausal status—were unavailable, making residual confounding likely. QAS parameters are correlated and partly pressure- or device-dependent; they should therefore be interpreted as a coherent pattern of functional alteration rather than as fully independent evidence. Although all examinations were performed by a single qualified sonographer, the exact software version and formal intra-observer repeatability metrics could not be recovered. CFSS requires external validation. Data collected in 2021–2022 may not represent broader contemporary populations. Finally, clinic measurements and documented history, without ambulatory or home monitoring, precluded confirmation of newly diagnosed hypertension.

Conclusions

High-normal blood pressure was associated with carotid functional abnormalities without a corresponding increase in QIMT after covariate adjustment. QAS may complement structural ultrasound assessment, but longitudinal studies with more complete covariate measurement are needed to establish temporal sequence, reproducibility, and prognostic value.

Abbreviations

BMI, body mass index; CC, compliance coefficient; CFSS, carotid functional stiffness score; CI, confidence interval; DC, distensibility coefficient; FDR, false discovery rate; PWV, pulse wave velocity; QAS, quantitative arterial stiffness; QIMT, quantitative intima–media thickness.

Declarations

Ethics approval and consent to participate

The Ethics Committee of Dongzhimen Hospital, Beijing University of Chinese Medicine approved this retrospective study involving human clinical data (approval number 2022DZMEC-338). The study was conducted in accordance with applicable ethical standards. The ethics committee waived the requirement for informed consent because the study retrospectively analyzed routinely collected clinical data.

Clinical trial number: not applicable.

Consent for publication

Not applicable. This manuscript does not contain identifiable individual-level data, images, or videos.

Availability of data and materials

The patient-level dataset generated and/or analysed during the current study is not publicly available because of patient privacy and institutional data-governance restrictions, but may be available from the corresponding author on reasonable request and subject to institutional approval. De-identified source data underlying the submitted figures are provided in Additional file 3, and the R analysis code is provided in Additional file 4.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

QX contributed to study conception and design, formal analysis, visualization, and preparation of the original manuscript draft. RX contributed to study design, development of the statistical analysis plan, interpretation and discussion of the results, and major revision of the manuscript. XZ contributed to data curation, interpretation of the results, and review and editing of the manuscript. FB, YW, YL, and RM contributed to data curation and interpretation of the results. YX contributed to supervision, funding

acquisition, and final review and approval. All authors read and approved the final manuscript and authorized its submission.

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Generative artificial intelligence-assisted tools were used only for language and readability editing. All authors reviewed and verified the final text and all reported results and take full responsibility for the manuscript.

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Figures

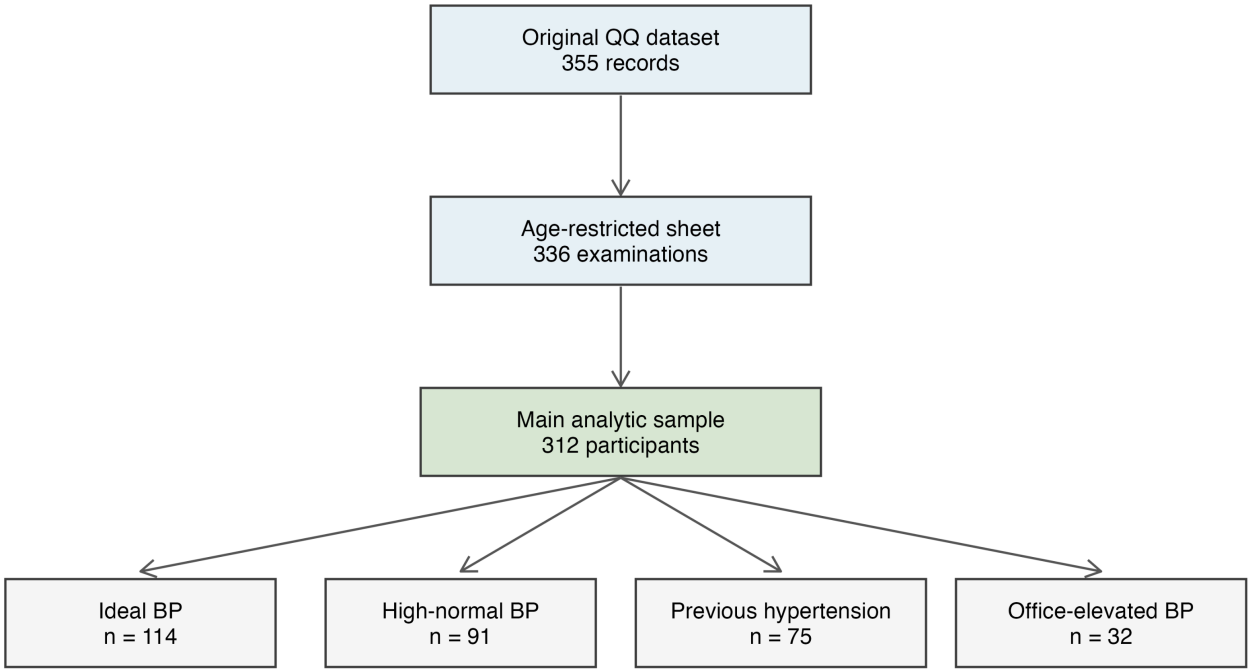


Figure 1

Study population flow

The original dataset contained 355 records, and the age-restricted worksheet contained 336 examinations. After subject-level de-duplication and retention of the first eligible examination for each participant, 312 adults were included and classified into four blood pressure groups

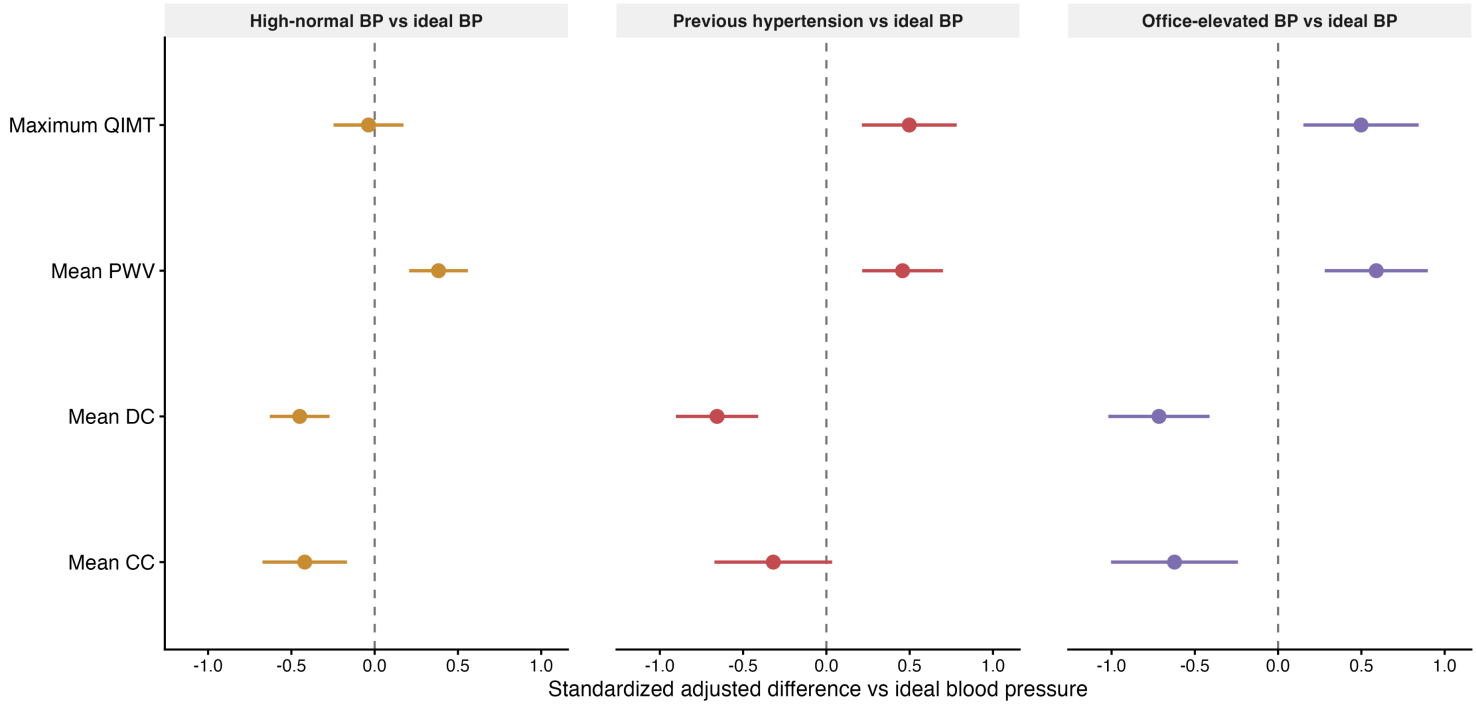


Figure 2

Adjusted carotid differences by blood pressure status

Standardized adjusted differences in carotid structural and functional measures by blood pressure status. Estimates were derived from multivariable linear models adjusted for age, sex, and body mass index, with ideal blood pressure as the reference. Error bars indicate 95% confidence intervals. CC, compliance coefficient; DC, distensibility coefficient; PWV, pulse wave velocity; QIMT, quantitative intima–media thickness

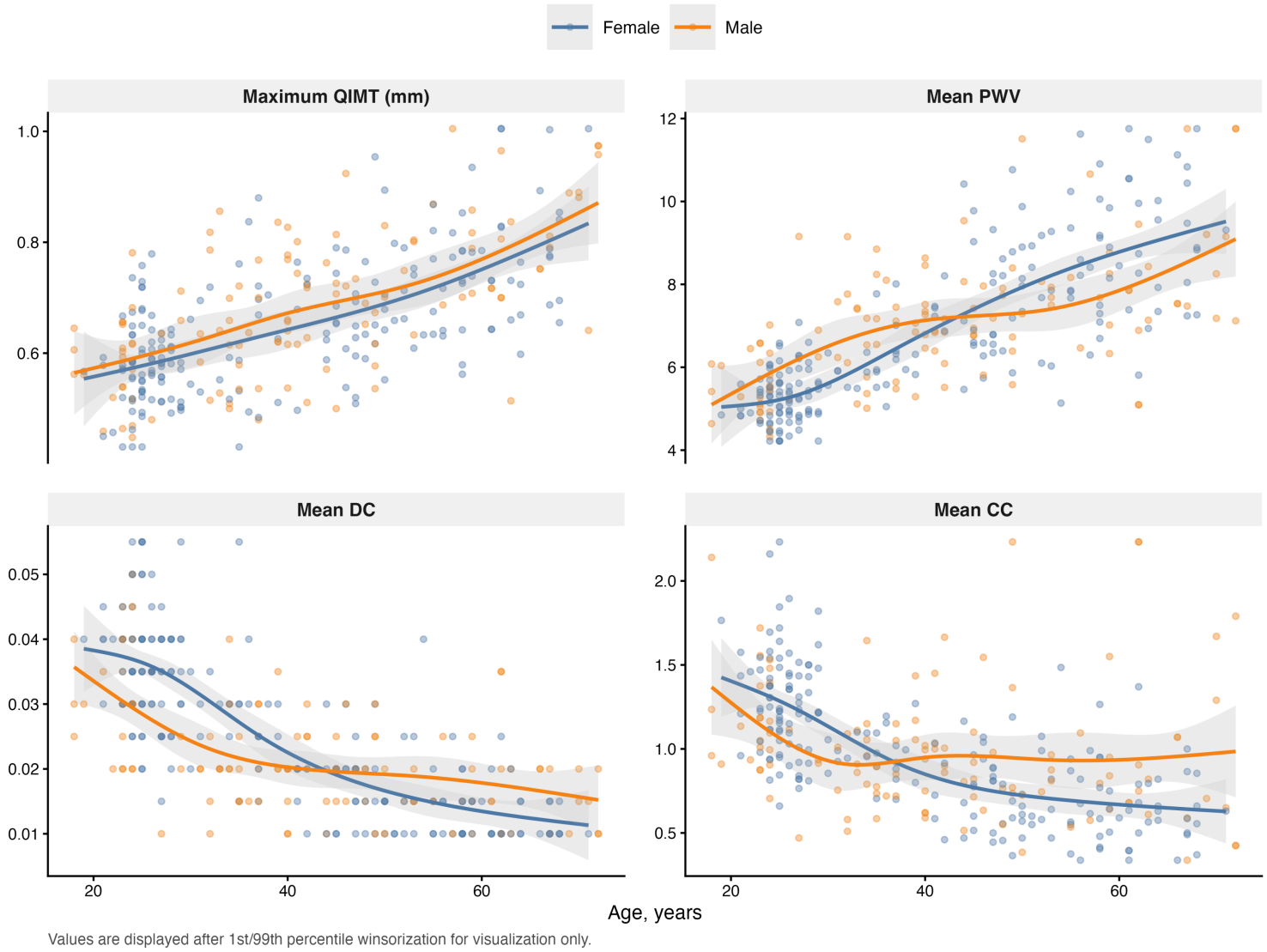


Figure 3

Age-related carotid structural and functional patterns

Age-related patterns in maximum QIMT and QAS-derived functional measures, stratified by sex. Natural-spline curves are shown with 95% confidence bands. Values were winsorized at the 1st and 99th percentiles for visualization only

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Additionalfile1Supplementarytables.xlsx
- Additionalfile4Analysiscode.zip
- Additionalfile3Figuresourcedata.xlsx
- Additionalfile2Supplementaryfigures.pdf