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Original Article

Association between Skeletal Muscle Mass and Ocular Perfusion Pressure in Glaucoma

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Purpose: This study aimed to investigate the relationship between body composition and glaucoma by analyzing the associations between anthropometric and ocular parameters.

Methods: A total of 494 eyes from 247 patients were reviewed from a general health examination database at a tertiary hospital. Anthropometric parameters were assessed using a multifrequency bioelectrical impedance device. Mean ocular perfusion pressure (MOPP) was calculated based on systolic and diastolic blood pressures and intraocular pressure (IOP). Retinal thickness and other ocular parameters were analyzed for their association with body composition.

Results: A total of 221 eyes from 221 patients, including 104 with glaucoma, were enrolled in the final analysis. The prevalence of sarcopenia was significantly higher in patients with glaucomatous damage than in those without (p = 0.025). Higher IOP showed significant associations with lower MOPP (p < 0.001), higher body mass index (BMI; p = 0.001), and higher waist to hip ratio (p = 0.001). Retinal thickness was not significantly associated with body composition parameters, including BMI and appendicular lean mass adjusted with squared height. Higher MOPP was significantly correlated with lower IOP (p < 0.001), higher BMI (p < 0.001), higher waist to hip ratio (p < 0.001), and higher appendicular lean mass divided by squared height (p = 0.009).

Conclusions: Skeletal muscle mass and BMI were significantly associated with MOPP. Since low MOPP is a known risk factor for glaucoma, its association with skeletal muscle mass may indicate a relationship between systemic muscle health, ocular blood perfusion, and glaucomatous damage. Further large-scale studies are needed to validate these associations between skeletal muscle mass and glaucoma and explore their clinical implications.

Key Words: Body mass index, Glaucoma, Optical coherence tomography, Perfusion, Skeletal muscle

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Glaucoma is a chronic progressive disease characterized by the degeneration of retinal ganglion cells and their axons, leading to irreversible visual field defects [1]. Established risk factors for glaucoma include advanced age, race, family history of glaucoma, and elevated intraocular pressure (IOP) [2,3]. Several studies indicate a strong relationship between ocular perfusion pressure (OPP) and glaucoma, particularly primary open-angle glaucoma

(POAG) [4,5].

OPP, which represents the difference between systemic blood pressure and IOP, plays a crucial role in optic nerve health [6]. Previous studies, including the Singapore Epidemiology of Eye Diseases study [4] and the Rotterdam Study [5], have demonstrated that lower OPP, often resulting from low blood pressure or elevated IOP, increases the risk of glaucoma development and progression. Reduced OPP may lead to compromised blood flow to the optic nerve, resulting in retinal ganglion cell damage. Maintaining an optimal OPP through appropriate blood pressure and IOP management is essential to reduce the risk of glaucoma progression [6].

Numerous factors are associated with glaucoma progression, and although research on the relationship between sarcopenia and glaucoma is still in its early stages, emerging studies suggest that sarcopenia, a condition marked by a decline in skeletal muscle mass and function, could negatively impact ocular health, particularly in glaucoma [7]. Sarcopenia has been linked to systemic factors such as reduced physical activity, poor nutrition, and metabolic dysregulation. These factors can contribute to autonomic nervous system imbalances [8] and impaired cardiovascular health through inflammation, insulin resistance, and physical inactivity [9], both of which have been implicated in glaucoma pathophysiology [10,11]. An autonomic nervous system imbalance can further contribute to the development or progression of glaucoma by disrupting the regulation of blood flow in the ocular tissues [10]. This is particularly significant because maintaining adequate blood flow is essential for preventing optic nerve damage in patients with glaucoma [11]. Moreover, prior research has demonstrated a relationship between body mass index (BMI) and cerebrospinal fluid pressure (CSFP), with implications for conditions such as POAG [12]. Low BMI and CSFP have been identified as risk factors for POAG, suggesting that body composition may influence ocular health [12]. Based on available literature, this study aimed to investigate the relationship between anthropometric parameters, particularly skeletal muscle mass, and ocular characteristics associated with glaucoma. By analyzing the correlation between systemic muscle mass and various ocular parameters, this study ought to explore the potential connection between sarcopenia and glaucoma.

Materials and Methods

Ethics statement

This retrospective cross-sectional study was approved by the Institutional Review Board of Hanyang University Seoul Hospital (No. 2024-12-049). The requirement for informed consent was waived due to the retrospective nature of the study. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Study participants

The study included patients who visited the glaucoma clinic between March 2021 and July 2023 and had undergone a health screening at the same hospital within 6 months prior to their visit. Patients with ocular conditions that could interfere with ophthalmic examination, such as severe cataracts, corneal opacity, or vitreous opacity, were excluded. Among study subjects with or without glaucomatous damage who met the inclusion criteria in both eyes, only the right eye was included in the final analysis.

Ocular examinations

All participants underwent a comprehensive ophthalmological examination, which included visual acuity testing, automated refraction assessment (ARK-1a, Nidek), slit-lamp examination, IOP measurement using noncontact tonometry, dilated fundus examination, and swept-source optical coherence tomography (DRI-OCT Triton, Topcon Inc). Systolic blood pressure (SBP) and diastolic blood pressure (DBP) were recorded on the day of ophthalmic examination to calculate mean OPP (MOPP), using the following equation [13]:

$$\mathrm{MOPP} = \frac{2}{3}\left(\mathrm{DBP} + \frac{\mathrm{SBP} - \mathrm{DBP}}{3}\right) - \mathrm{IOP}$$

The peripapillary retinal nerve fiber layer (RNFL), macular ganglion cell-inner plexiform layer (mGCIPL), and macular ganglion cell complex (mGCC) thicknesses were measured using swept-source optical coherence tomography, and the mean values of these parameters were used in the analysis. For patients suspected of having glaucoma, standard automated perimetry was conducted using a

Humphrey Field Analyzer II or III (Carl Zeiss Meditec Inc) to assess glaucomatous visual field defects.

Glaucoma was diagnosed by a glaucoma specialist (WJL) using the International Society for Geographical and Epidemiological Ophthalmology criteria [14]: (1) a horizontal or vertical cup-disc ratio >0.7 or cup-disc asymmetry >0.2 (both values exceeding the 97.5th percentile for the normal population), or focal glaucomatous disc changes (disc hemorrhage, neuroretinal rim notching, marked sloping of rim tissue, with a narrowest remaining rim <0.1 disc diameter), along with a glaucomatous visual field defect corresponding to optic disc abnormalities; (2) a horizontal or vertical cup-disc ratio >0.8 or cup-disc asymmetry >0.3 (both values exceeding the 99.5th percentile for the normal population), or focal glaucomatous disc changes accompanied by a focal RNFL defect.

Anthropometric examinations

During health screening, all participants underwent anthropometric analysis using a multifrequency bioelectrical impedance analysis (MF-BIA) device (InBody S10, InBody Co Ltd). Systemic blood pressure and resting heart rate were measured using a digital tensiometer (HBP-9030, Omron).

To assess sarcopenia and muscle mass, all body composition parameters measured by MF-BIA, including the InBody Score, total body protein, mineral content, appendicular lean mass (ALM), BMI, abdominal fat percentage, waist to hip ratio, and limb weight, were recorded. The InBody Score is a composite numerical value derived from MF-BIA that reflects overall body composition based on fat mass and lean body mass, with higher scores indicating lower fat mass to lean mass ratio. ALM, representing the lean mass of the arms and legs, was calculated by summing the weights of the limbs. ALM divided by squared height (ALM/ht^2) is commonly used as a diagnostic criterion for sarcopenia. Although sarcopenia criteria vary, ranging from ALM/ht^2 of <7.0 to <7.23 kg/m^2 in men and <5.4 to <5.67 kg/m^2 in women [15–18], the present study adopted the International Working Group on Sarcopenia criteria, defining sarcopenia as ALM/ht^2 of <7.23 kg/m^2 for men and <5.67 kg/m^2 for women (Supplementary Table 1) [16].

Statistical analysis

Demographic and clinical characteristics were compared between patients with and without glaucomatous damage using independent *t*-test for normally distributed continuous variables and Fisher exact test for categorical variables. Linear regression analysis was conducted to assess associations between ocular parameters (RNFL, mGCIPL, mGCC, MOPP, and IOP) and body composition. Variables with *p*-values of <0.05 in the univariable model were considered possible explanatory variables and included in the multivariable model. To diagnose multicollinearity between variables, the variance inflation factor (VIF) was obtained from a multivariable linear regression model that included all potential explanatory variables. Variables with a VIF above 3.3 were considered to exhibit multicollinearity [19]; therefore, separate final multivariable linear regression models using a stepwise approach were performed to address the highly intercorrelated variables. All statistical analyses were performed using IBM SPSS ver. 27 (IBM Corp).

Results

Demographics and clinical characteristics of the study participants

Of the 247 eyes initially enrolled, 26 were excluded due to ocular diseases that could interfere with examination, such as severe cataracts and age-related macular degeneration. Consequently, a total of 221 eyes from 221 patients, including 117 eyes without glaucomatous damage, were included in the final analysis.

Table 1 presents the demographic and clinical characteristics of the patients. Patients with glaucomatous damage were significantly older ($p = 0.003$), used more glaucoma medications ($p < 0.001$), had thinner RNFL, mGCIPL, and mGCC (all $p < 0.001$), and exhibited higher IOP ($p = 0.021$). Anthropometric parameters, including the InBody Score, protein mass, mineral mass, BMI, waist to hip ratio, ALM, and ALM/ht^2, did not differ significantly between the two groups. However, when the sarcopenia criteria based on ALM/ht^2 and sex were applied, the glaucoma group had a significantly higher prevalence of sarcopenia than the control group ($p = 0.025$).

Table 1. Clinical characteristics of patients with and without glaucoma

Characteristic	Without glaucoma (n = 117)	With glaucoma (n = 104)	*p*-value
Age (yr)	52.78 ± 12.10	57.68 ± 12.38	0.003*
Sex			0.625
Male	58 (49.6)	55 (52.9)	
Female	59 (50.4)	49 (47.1)	
No. of glaucoma medications	0	0.52 ± 0.89	<0.001*
Hypertension	36 (30.8)	25 (24.0)	0.067
Diabetes mellitus	25 (21.4)	11 (10.6)	0.099
RNFL thickness (μm)	105.41 ± 11.70	88.70 ± 18.93	<0.001*
mGCIPL thickness (μm)	71.94 ± 8.70	65.57 ± 6.07	<0.001*
mGCC thickness (μm)	108.64 ± 8.91	101.19 ± 9.34	<0.001*
Intraocular pressure (mmHg)	15.55 ± 3.18	16.69 ± 4.13	0.021*
Mean ocular perfusion pressure (mmHg)	47.44 ± 8.37	46.04 ± 8.14	0.212
InBody Score	69.89 ± 5.61	70.70 ± 5.41	0.279
Protein mass (kg)	9.24 ± 2.73	9.27 ± 2.17	0.929
Mineral mass (kg)	3.18 ± 0.77	3.21 ± 0.70	0.770
Body mass index (kg/m^2)	24.10 ± 3.08	23.60 ± 3.20	0.234
Waist to hip ratio	0.88 ± 0.05	0.88 ± 0.05	0.198
ALM (kg)	25.32 ± 5.74	25.96 ± 6.57	0.443
ALM/ht^2 (kg/m^2)	6.92 ± 1.02	6.95 ± 1.17	0.877
Sarcopenia	20 (17.1)	31 (29.8)	0.025*

Values are expressed as mean ± standard deviation or number (%).
RNFL = retinal nerve fiber layer; mGCIPL = macular ganglion cell-inner plexiform layer; mGCC = macular ganglion cell complex; ALM = appendicular lean mass; ALM/ht^2 = appendicular lean mass divided by squared height.
*Statistically significant ($p < 0.05$).

Relationship between IOP and anthropometric parameters

The association between IOP and body composition parameters was assessed (Table 2). IOP was significantly correlated with MOPP (β = −0.128, $p < 0.001$), BMI (β = 0.157, $p = 0.048$), and waist to hip ratio (β = 9.990, $p = 0.043$). However, no significant correlation was observed between IOP and other body composition parameters. Due to high collinearity between BMI (VIF, 5.006) and waist to hip ratio (VIF, 5.039) (Supplementary Table 2), two separate multivariable models were used. In model 1, lower MOPP (β = −0.151, $p < 0.001$) and higher BMI (β = 0.253, $p = 0.001$) were significantly associated with higher IOP. In model 2, lower MOPP (β = −0.139, $p < 0.001$) and higher waist to hip ratio (β = 15.921, $p = 0.001$) were significantly correlated with higher IOP.

Relationship between retinal thickness parameters and anthropometric parameters

The relationships between retinal thickness parameters (RNFL, mGCIPL, and mGCC) and anthropometric factors were analyzed (Table 3). No significant association was observed between retinal thickness parameters and anthropometric parameters, including InBody Score, protein mass, mineral mass, BMI, waist to hip ratio, ALM, or ALM/ht^2 (all $p > 0.05$).

Relationship between MOPP and anthropometric parameters

The association between MOPP and body composition parameters was examined using univariable and multivariable linear regression analyses (Table 4). MOPP was significantly correlated with IOP (β = −0.640, $p < 0.001$), protein

Table 2. Factors associated with intraocular pressure

Factor	Univariable analysis			Multivariable analysis					
				Model 1			Model 2		
	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value
Age (yr)	0.030	–0.009 to 0.069	0.133	-	-	-	-	-	-
Male sex	–0.204	–1.186 to 0.777	0.682	-	-	-	-	-	-
No. of glaucoma medications	0.148	–0.593 to 0.890	0.694	-	-	-	-	-	-
Hypertension	0.651	–0.443 to 1.746	0.242	-	-	-	-	-	-
Diabetes mellitus	0.068	–1.277 to 1.412	0.921	-	-	-	-	-	-
RNFL thickness (μm)	–0.009	–0.037 to 0.019	0.528	-	-	-	-	-	-
mGCIPL thickness (μm)	–0.010	–0.070 to 0.050	0.749	-	-	-	-	-	-
mGCC thickness (μm)	–0.007	–0.057 to 0.043	0.795	-	-	-	-	-	-
MOPP (mmHg)	–0.128	–0.185 to –0.071	<0.001*	–0.151	–0.208 to –0.093	<0.001*	–0.139	–0.196 to –0.082	<0.001*
InBody Score	0.009	–0.078 to 0.096	0.838	-	-	-	-	-	-
Protein mass (kg)	0.034	–0.164 to 0.233	0.736	-	-	-	-	-	-
Mineral mass (kg)	0.135	–0.533 to 0.802	0.691	-	-	-	-	-	-
BMI (kg/m^2)	0.157	0.002 to 0.312	0.048*	0.253	0.102 to 0.405	0.001*	-	-	-
Waist to hip ratio	9.990	0.297 to 19.684	0.043*	-	-	-	15.921	6.362 to 25.480	0.001*
ALM (kg)	0.025	–0.055 to 0.105	0.533	-	-	-	-	-	-
ALM/ht^2 (kg/m^2)	0.218	–0.232 to 0.669	0.341	-	-	-	-	-	-
Sarcopenia	–0.596	–1.758 to 0.566	0.313	-	-	-	-	-	-

Model 1, adjusted for MOPP and BMI. Model 2, adjusted for MOPP and waist to hip ratio.
CI = confidence interval; RNFL = retinal nerve fiber layer; mGCIPL = macular ganglion cell-inner plexiform layer; mGCC = macular ganglion cell complex; MOPP = mean ocular perfusion pressure; BMI = body mass index; ALM = appendicular lean mass; ALM/ht^2 = appendicular lean mass divided by squared height.
*Statistically significant ($p < 0.05$).

Table 3. Factors associated with optical coherence tomography retinal thickness parameters, including RNFL, mGCIPL, and mGCC thickness

Factor	RNFL thickness (μm)			mGCIPL thickness (μm)			mGCC thickness (μm)		
	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value
Age (yr)	–0.160	–0.347 to 0.027	0.094	–0.050	–0.137 to 0.037	0.260	–0.073	–0.178 to 0.031	0.168
Male sex	4.507	–0.134 to 9.147	0.057	1.307	–0.867 to 3.480	0.237	–0.153	–2.764 to 2.459	0.908
No. of glaucoma medications	–13.218	–16.283 to –10.153	<0.001*	–4.057	–5.613 to –2.501	<0.001*	–6.021	–7.823 to –4.219	<0.001*
Hypertension	–1.277	–6.507 to 3.953	0.631	–0.777	–3.213 to 1.659	0.530	–1.195	–4.111 to 1.720	0.420
Diabetes mellitus	0.266	–6.141 to 6.673	0.935	2.448	–0.519 to 5.416	0.105	3.443	–0.103 to 6.989	0.057
RNFL thickness (μm)	-	-	-	0.272	0.222 to 0.323	<0.001*	0.335	0.276 to 0.395	<0.001*
mGCIPL thickness (μm)	1.255	1.023 to 1.486	<0.001*	-	-	-	0.891	0.784 to 0.998	<0.001*
mGCC thickness (μm)	1.077	0.886 to 1.268	<0.001*	0.621	0.547 to 0.695	<0.001*	-	-	-
Intraocular pressure (mmHg)	–0.203	–0.838 to 0.431	0.528	–0.048	–0.344 to 0.248	0.749	–0.047	–0.401 to 0.307	0.795
MOPP (mmHg)	–0.046	–0.329 to 0.238	0.751	–0.098	–0.230 to 0.033	0.141	–0.158	–0.315 to 0.000	0.050
InBody Score	0.024	–0.402 to 0.451	0.910	0.051	–0.147 to 0.250	0.612	0.109	–0.129 to 0.346	0.368
Protein mass (kg)	–0.203	–1.149 to 0.744	0.674	–0.177	–0.617 to 0.264	0.430	0.023	–0.505 to 0.552	0.930
Mineral mass (kg)	–0.807	–3.988 to 2.374	0.618	–0.787	–2.266 to 0.693	0.296	–0.045	–1.821 to 1.732	0.961
Body mass index (kg/m^2)	0.177	–0.570 to 0.924	0.641	–0.055	–0.353 to 0.343	0.979	–0.101	–0.517 to 0.316	0.634
Waist to hip ratio	37.143	–1.059 to 84.875	0.127	8.095	–14.240 to 30.431	0.476	1.992	–24.786 to 28.769	0.884
ALM (kg)	–0.174	–0.555 to 0.207	0.369	–0.093	–0.271 to 0.084	0.301	0.015	–0.198 to 0.228	0.890
ALM/ht^2 (kg/m^2)	–1.243	–3.388 to 0.901	0.254	–0.465	–1.465 to 0.536	0.361	–0.050	–1.250 to 1.150	0.935
Sarcopenia	–3.643	–9.174 to 1.887	0.196	–0.890	–3.474 to 1.694	0.498	–0.760	–3.857 to 2.337	0.629

RNFL = retinal nerve fiber layer; mGCIPL = macular ganglion cell-inner plexiform layer; mGCC = macular ganglion cell complex; CI = confidence interval; MOPP = mean ocular perfusion pressure; ALM = appendicular lean mass; ALM/ht^2 = appendicular lean mass divided by squared height.
*Statistically significant ($p < 0.05$).

Table 4. Factors associated with mean ocular perfusion pressure

Factor	Univariable analysis			Multivariable analysis														
				Model 1			Model 2			Model 3			Model 4			Model 5		
	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value	β	95% CI	*p*-value
Age (yr)	–0.005	–0.093 to 0.083	0.912	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Male sex	–0.934	–3.130 to 1.261	0.402	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
No. of glaucoma medications	0.050	–1.601 to 1.701	0.952	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hypertension	2.609	0.189 to 5.028	0.035*	2.918	0.614 to 5.221	0.013*	2.867	0.570 to 5.164	0.015	2.372	0.112 to 4.633	0.040*	Dropped†	-	-	2.724	0.424 to 5.023	0.020*
Diabetes mellitus	–0.974	–3.964 to 2.016	0.521	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RNFL thickness (μm)	–0.010	–0.073 to 0.052	0.751	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
mGCIPL thickness (μm)	–0.100	–0.234 to 0.034	0.141	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
mGCC thickness (μm)	–0.111	–0.221 to 0.000	0.050	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IOP (mmHg)	–0.640	–0.926 to –0.355	<0.001*	–0.677	–0.956 to –0.398	<0.001*	–0.679	–0.957 to –0.400	<0.001*	–0.741	–1.015 to –0.468	<0.001*	–0.687	–0.968 to –0.405	<0.001*	–0.692	–0.970 to –0.414	<0.001*
InBody Score	–0.075	–0.273 to 0.122	0.453	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Protein mass (kg)	0.461	0.020 to 0.901	0.040*	0.442	0.026 to 0.857	0.037*	-	-	-	-	-	-	-	-	-	-	-	-
Mineral mass (kg)	1.788	0.311 to 3.265	0.018*	-	-	-	1.716	0.323 to 3.110	0.016*		-	-	-	-	-	-	-	-
BMI (kg/m^2)	0.637	0.297 to 0.978	<0.001*	-	-	-	-	-	-	0.679	0.354 to 1.003	<0.001*	-	-	-	-	-	-
Waist to hip ratio	42.709	21.148 to 64.269	<0.001*	-	-	-	-	-	-	-	-	-	48.625	27.990 to 69.260	<0.001*	-	-	-
ALM (kg)	0.246	0.070 to 0.423	0.006*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ALM/ht^2 (kg/m^2)	1.279	0.283 to 2.275	0.012*	-	-	-	-	-	-	-	-	-	-	-	-	1.265	0.321 to 2.209	0.009*
Sarcopenia	–3.311	–5.902 to –0.760	0.011*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Model 1, adjusted for IOP and protein mass. Model 2, adjusted for IOP and mineral mass. Model 3, adjusted for IOP and BMI. Model 4, adjusted for IOP and waist to hip ratio. Model 5, adjusted for IOP and ALM/ht^2.

CI = confidence interval; RNFL = retinal nerve fiber layer; mGCIPL = macular ganglion cell-inner plexiform layer; mGCC = macular ganglion cell complex; IOP = intraocular pressure; BMI = body mass index; ALM = appendicular lean mass; ALM/ht^2 = appendicular lean mass divided by squared height.

*Statistically significant ($p < 0.05$); †In model 4, hypertension was excluded from the final multivariable model via stepwise selection.

mass (β = 0.461, p = 0.040), mineral mass (β = 1.788, p = 0.018), BMI (β = 0.637, p < 0.001), waist to hip ratio (β = 42.709, p < 0.001), ALM (β = 0.246, p = 0.006), ALM/ht^2 (β = 1.279, p = 0.012), and sarcopenia (β = −3.311, p = 0.011).

Among the muscle mass variables (ALM, ALM/ht^2, sarcopenia), ALM/ht^2, which accounts for individual size variation and is used as the criterion for sarcopenia [15,16,18], was selected for the final multivariable analysis. Five final multivariable models were developed to account for multicollinearity between body composition parameters (protein mass VIF, 20.881; mineral mass VIF, 24.984; BMI VIF, 6.451; waist to hip ratio VIF, 5.377; ALM/ht^2 VIF, 4.225) (Supplementary Table 3). In model 1, higher protein (β = 0.442, p = 0.037), lower IOP (β = −0.677, p < 0.001), and the presence of hypertension (β = 2.918, p = 0.013) were significantly correlated with higher MOPP. In

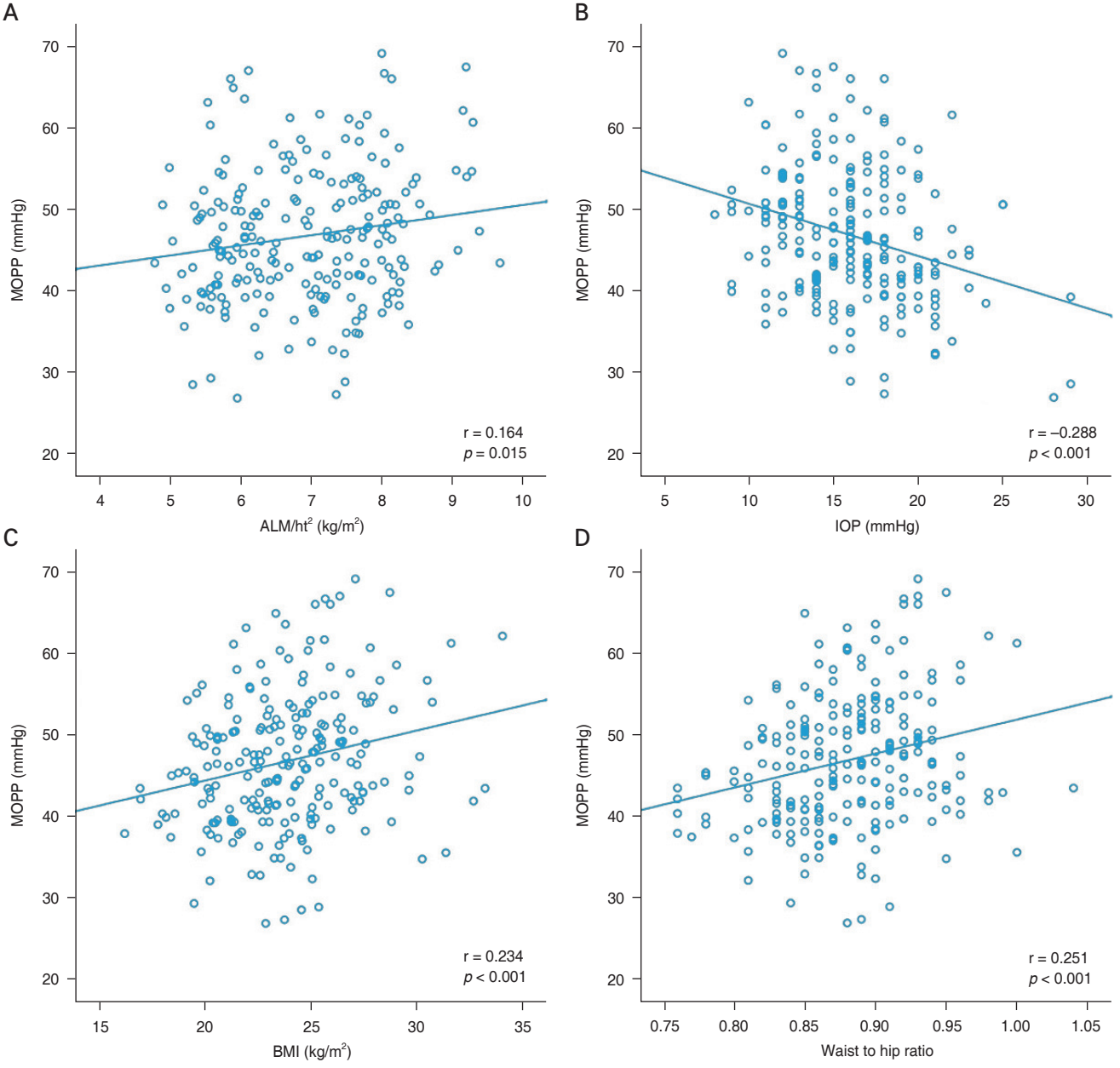

Fig. 1. Scatter plots illustrating the relationships between mean ocular perfusion pressure (MOPP) and anthropometric parameters, as well as intraocular pressure (IOP). (A) Appendicular lean mass divided by squared height (ALM/ht^2), (B) IOP, (C) body mass index (BMI), and (D) waist to hip ratio were significantly correlated with MOPP (all p < 0.05).

model 2, higher mineral mass (β = 1.716, $p = 0.016$), lower IOP (β = −0.679, $p < 0.001$), and the presence of hypertension (β = 2.867, $p = 0.015$) were significantly correlated with higher MOPP. In model 3, higher BMI (β = 0.679, $p < 0.001$), lower IOP (β = −0.741, $p < 0.001$), and the presence of hypertension (β = 2.372, $p = 0.040$) were significantly correlated with higher MOPP. In model 4, higher waist to hip ratio (β = 48.625, $p < 0.001$) and lower IOP (β = −0.687, $p < 0.001$) were associated with higher MOPP. In model 5, higher ALM/ht^2 (β = 1.265, $p = 0.009$), lower IOP (β = −0.692, $p < 0.001$), and the presence of hypertension (β = 2.724, $p = 0.020$) were significantly correlated with higher MOPP.

Fig. 1A–1D illustrates the correlation between MOPP and anthropometric parameters as well as IOP, demonstrating that higher ALM/ht^2 ($p = 0.015$), lower IOP ($p < 0.001$), higher BMI ($p < 0.001$), and greater waist to hip ratio ($p < 0.001$) were significantly associated with higher MOPP.

Discussion

This study investigated the associations between anthropometric parameters, including muscle mass, and ocular parameters related to glaucoma. The findings demonstrated that ALM/ht^2 was significantly associated with MOPP, whereas BMI and the waist to hip ratio were correlated with IOP and MOPP. These results suggest that body composition, particularly BMI and ALM/ht^2, is associated with higher MOPP or IOP, highlighting a potential link between systemic muscle health and ocular blood flow dynamics.

Vascular dysregulation and unstable OPP are critical factors associated with the progression of open-angle glaucoma, particularly normal tension glaucoma [20]. Considering that normal tension glaucoma is the most prevalent form of open-angle glaucoma in East Asia [21,22], maintaining an optimal OPP may be important in preventing disease progression [6,20,23]. Given that SBP and DBP are major contributors to OPP, systemic circulation and glaucoma cannot be considered independently. Previous studies have established associations between glaucoma and chronic vascular diseases, such as hypertension and diabetes [24,25], which impact systemic circulation and OPP [20]. The association between systemic vascular health and OPP is well documented, and because low OPP is a significant risk factor for glaucoma progression [20], evaluating anthropometric factors related to OPP could provide valuable insights into the pathophysiology and treatment of glaucoma.

In the present study, analysis of factors related to MOPP revealed a significant correlation with ALM/ht^2, even after adjusting for confounding factors. Moreover, the prevalence of sarcopenia was significantly higher in the glaucoma group, whereas other body composition parameters did not differ between patients with glaucomatous damage and those without. This suggests a potential association between glaucomatous damage and lower limb muscle mass. However, no significant correlations were found between muscle mass parameters and RNFL, mGCIPL, or mGCC thicknesses, indicating that systemic muscle mass may not directly influence the structural changes in the retinal layers observed in glaucoma. Instead, muscle mass may contribute to glaucomatous damage through mechanisms unrelated to direct retinal structural alterations. Given the observed correlation between ALM/ht^2 and MOPP, systemic health factors such as muscle mass and physical fitness may play a role in managing and preventing glaucoma progression by improving ocular blood flow.

Although the relationship between skeletal muscle mass and OPP or glaucoma has not been extensively studied, some investigations have explored the link between exercise and glaucoma [26,27]. Lin et al. [26] analyzed a South Korean population and found that moderate-intensity exercise is protective against glaucoma in men. Similarly, Yip et al. [27] demonstrated that high levels of habitual physical activity, either occupational or recreational, are associated with a reduced risk of low OPP, suggesting a potential protective effect of physical activity against glaucoma development. Exercise has been shown to transiently lower IOP while increasing systemic blood pressure, thereby elevating OPP [28]. Moreover, higher physical activity levels have been linked to a reduced risk of arterial stiffness [29], preventing a decrease in arterial compliance and maintaining an optimal OPP. Consistent with previous studies, the results of the present study suggest the correlation between skeletal muscle mass and OPP, and support the protective role of maintaining an adequate level of muscle mass, either through exercise or physical activity, in glaucoma. This study underscores the potential long-term benefits of physical activity in preventing glaucoma progression and provides a basis for glaucoma specialists to advocate for

maintaining skeletal muscle mass in at-risk patients. Future research is needed to elucidate the specific mechanisms linking skeletal muscle mass with ocular perfusion and determine whether muscle mass may influence other ocular parameters beyond MOPP, potentially leading to novel therapeutic approaches addressing both systemic and ocular health.

Previous studies have also reported an association between higher BMI and increased MOPP or IOP [30–34]. Cakmak et al. [30] identified a positive linear relationship between BMI and both IOP and MOPP, whereas Ramya et al. [31] found that individuals with a BMI exceeding 25.0 kg/m^2 exhibited higher MOPP and IOP than those with a BMI between 18.0 and 22.9 kg/m^2. A study conducted on a South Korean cohort similarly demonstrated a correlation between higher BMI, increased waist circumference, and elevated IOP [32]. Consistent with these findings, the present study revealed a significant association between higher BMI and increased MOPP, as well as higher IOP. However, there is ongoing debate regarding whether obesity exerts a protective [35–37] or harmful [38] effect on glaucoma. In this study, no significant differences were found in BMI or waist to hip ratio between the glaucoma and control groups. The association of BMI with high MOPP (a protective factor) and high IOP (a harmful factor), without showing a definitive difference in the glaucoma group, may be attributed to its correlation with CSFP and the inherent ambiguity of BMI. Previous research has established a positive correlation between BMI and CSFP [12,39], suggesting that individuals with higher BMI may also exhibit elevated CSFP. The translaminar pressure gradient, defined as the difference between the IOP and CSFP, is implicated in glaucomatous optic neuropathy [40]. Individuals with higher BMI, who typically have both elevated IOP and increased CSFP, may exhibit a translaminar pressure gradient comparable to those with lower BMI, potentially mitigating the differences in glaucomatous prevalence between groups. Moreover, BMI is influenced by fat and muscle mass, making it difficult to differentiate between them. Consequently, individuals with greater muscle mass may also be classified as having a higher BMI.

A key strength of this study was the use of MF-BIA to assess muscle mass and investigate its relationship with glaucoma. One of the primary advantages of using MF-BIA is its noninvasive nature, allowing for the accurate measurement of muscle mass, body fat, and body water with minimal burden on participants. This technique enables quick and reliable body composition assessments without requiring invasive or time-consuming procedures. Additionally, this study used health check-up data rather than data of tertiary hospital clinic patients, reducing potential selection bias. Often, patients who seek care at tertiary hospitals present with preexisting conditions or specific health concerns, which can introduce bias. By utilizing data from routine health screenings, the study results are more generalizable and applicable to a broader population. Moreover, MF-BIA facilitates large-scale data collection, providing opportunities for future longitudinal studies and large cohort analyses. The inclusion of MF-BIA data in this context could enhance our understanding of the relationship between muscle mass and ocular health, fostering further exploration of these associations in large and diverse populations.

Despite these strengths, this study has several limitations. First, this study used a cross-sectional design rather than a prospective design, which may have allowed for stronger causal inferences between muscle mass and glaucoma. Furthermore, the current design limited the ability to fully understand the directionality of the observed relationships and their long-term effects. Second, the relatively small sample size limits the generalizability of the findings and reduces the statistical power to detect subtle but potentially significant associations. Third, this study did not account for adjustment for factors, including central corneal thickness, axial length, or refractive error, which may influence IOP measurements. Future research incorporating larger prospective cohorts and adjusting for these additional variables is warranted to confirm these findings and further elucidate the underlying mechanisms linking muscle mass and ocular health.

In conclusion, this study highlights a potential correlation between body composition parameters and ocular perfusion, particularly with respect to MOPP. The significant association between higher MOPP and greater skeletal muscle mass suggests that maintaining or increasing muscle mass may be beneficial in preventing glaucoma progression. Further studies are necessary to elucidate the complex vascular mechanisms linking body composition parameters to glaucomatous damage.

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Supplementary Materials

Supplementary Table 1. ALM cutoffs in sarcopenia diagnosis

Supplementary Table 2. Regression coefficients and collinearity statistics of multivariable linear regression model for intraocular pressure

Supplementary Table 3. Regression coefficients and collinearity statistics of multivariable linear regression model for mean ocular perfusion pressure

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Supplementary Table 1. ALM cutoffs in sarcopenia diagnosis

Sarcopenia criteria	ALM/ht^2 (kg/m^2)		ALM / BMI	
	Men	Women	Men	Women
EWGSOP2	<7.0	<5.5	NA	NA
AWGS	<7.0	<5.4	NA	NA
FNIH	NA	NA	<0.789	<0.512
IWGS	<7.23	<5.67	NA	NA

ALM = appendicular lean mass; ALM/ht^2 = appendicular lean mass divided by squared height; BMI = body mass index; EWGSOP2 = European Working Group on Sarcopenia in Older People 2; NA = not available; AWGS = Asian Working Group for Sarcopenia; FNIH = Foundation for the National Institutes of Health; IWGS = International Working Group on Sarcopenia.

Supplementary Table 2. Regression coefficients and collinearity statistics of multivariable linear regression model for intraocular pressure

Variable	Multivariable analysis			Collinearity statistic	
	β	95% CI	*p*-value	Tolerance	VIF
Mean ocular perfusion pressure (mmHg)	–0.141	–0.198 to –0.083	<0.001*	0.936	1.069
Body mass index (kg/m^2)	0.093	–0.230 to 0.416	0.572	0.200	5.006
Waist to hip ratio	10.558	–10.208 to 31.325	0.317	0.198	5.039

CI = confidence interval; VIF = variance inflation factor.
*Statistically significant ($p < 0.05$).

Supplementary Table 3. Regression coefficients and collinearity statistics of multivariable linear regression model for mean ocular perfusion pressure

Variable	Multivariable analysis			Collinearity statistic	
	β	95% CI	*p*-value	Tolerance	VIF
Hypertension	2.019	–0.283 to 4.320	0.085	0.942	1.062
Intraocular pressure (mmHg)	–0.700	–0.982 to –0.417	<0.001*	0.973	1.027
Protein mass (kg)	–1.058	–2.907 to 0.792	0.261	0.048	20.881
Mineral mass (kg)	4.497	–2.303 to 11.298	0.194	0.040	24.984
Body mass index (kg/m^2)	0.183	–0.627 to 0.993	0.656	0.155	6.451
Waist to hip ratio	32.653	–14.708 to 80.013	0.176	0.186	5.377
ALM/ht^2 (kg/m^2)	–0.411	–2.306 to 1.484	0.669	0.237	4.225

CI = confidence interval; VIF = variance inflation factor; ALM/ht^2 = appendicular lean mass divided by squared height.
*Statistically significant ($p < 0.05$).