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Adult Human Ocular Volume: Scaling to Body Size and Composition

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Abstract

Objectives: Little is currently known on how human ocular volume (OV) relates to body size or composition across adult men and women. This gap was filled in an exploratory study on the path to developing anthropological and physiological models by measuring OV in young healthy adults and related brain, head, and body mass along with major body components.

Methods: Thirty-six men and 44 women, ages 20-35 yrs, were evaluated with magnetic resonance imaging and dual-energy X-ray absorptiometry that provided estimates of OV, brain, head, fat, lean soft tissue (LST), and bone mineral mass. Associations between OV and other components were evaluated first followed by development of allometric models relating OV and other components to body size as defined by stature.

Results: Mean OV was non-significantly larger in men (X ± SD; 6.35 ± 0.69 cm^3) than in women (6.26 ± 0.53 cm^3; P=NS), although OV in women was significantly larger relative to brain and head mass than in men (both p<0.001). While larger body components (e.g., LST) scaled to height with powers as expected from previous studies, these associations for OV were weak or non-significant. Our findings are consistent with a systematic review of earlier autopsy, surgical, and imaging OV studies.

Conclusions: Unlike most other lean tissues and organs, the absolute eye volume is largely independent of a person's sex and body size or composition. As a small anatomic body component, the adult human eye appears to function within relatively narrow dimensional constraints. Future larger sample studies are needed to explore age and racial/ethnic differences in OV.

Keywords: Eye; Vision; Allometry; Body composition; Reference human

Introduction

The human eye is among the smallest body organs, both eyes accounting for about 0.02% of body mass [1]. As a key sensory organ, the eye is intimately linked with optic nuclei within the brain and through that neural pathway with a vast array of central nervous system processes. Despite being accessible by post-mortem dissection [2] and modern imaging methods [3,4], very little information is available on the associations between ocular volume and brain volume along with related head and body mass. While early studies explored some of these associations [2], data is remarkably limited. The lack of this information leaves a large gap when assembling integrated anthropological [5-8], physiological [9-12], and body composition [13] models. Topics such as the expanded Reference Human concept [14] or treatises on the human head [15] have a modest set of ocular volume reports from which to develop models accounting for organ-tissue body size relations. The adult human body size scaling relations are well established for large organs and tissues such skeletal muscle, bone, liver, brain, and heart [9,16-19].

Does ocular volume differ significantly across healthy men and women as does stature and related whole-body lean soft tissue (LST) mass [10,17], of which the eye is a part? Does adult human ocular volume scales similarly to body size (i.e., height) as do other LST components, including brain mass [12]? Is ocular volume (or mass) a constant proportion of head mass in men and women?

Definitive answers to these questions are lacking, although a number of studies over the last century have specifically examined ocular volume and related dimensions in adult men and women. Most of these studies include relatively small samples [20-24] apply different methods for measuring ocular volume (i.e., ultrasound, computed tomography [CT], and magnetic resonance imaging [MRI]) or mass (i.e., direct weighing of enucleated surgical or autopsy specimens), and often provide very few additional subject measurements (e.g., cranial capacity as a proxy for brain volume) outside of those related to eye dimensions.

Here, we endeavored to begin answering these questions by intensively evaluating a cohort of healthy young men and women with ocular volume and brain volume measured by MRI and body composition (i.e., LST and other components) quantified using dual-energy X-ray absorptiometry (DXA). The associations between ocular volume and these components, including total body mass, were examined first and then we established their allometric relations with body size as defined by stature [19]. In the concluding section, we provide a systematic review of the available literature on ocular volume in healthy adults.

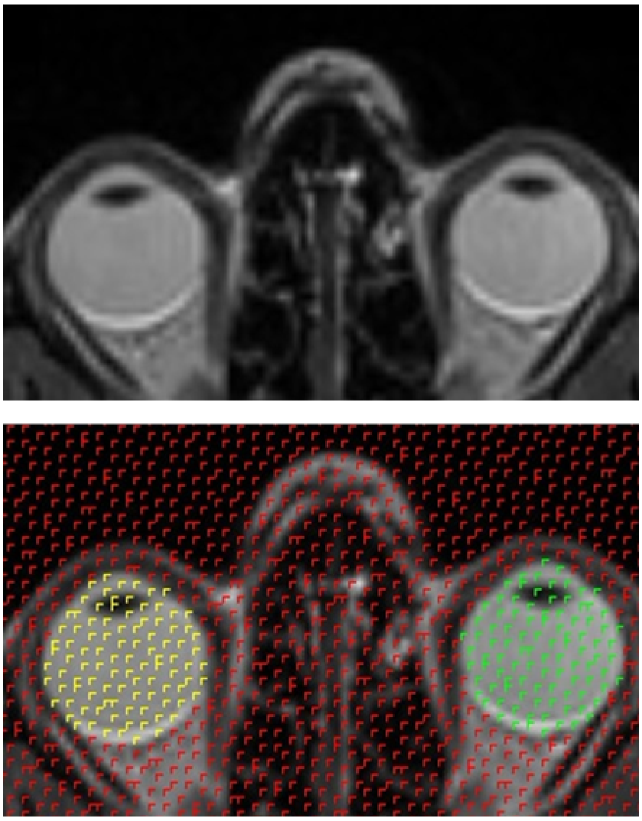

Figure 1: Grid points on the eye.

Materials and Methods

Experimental design

Subjects were participants in the Insight Study [25] that was designed as a prospective investigation of healthy young adults. The subjects reported in the current study participated in the comprehensive baseline evaluation. The study was approved by the center's Institutional Review Board and all subjects signed an informed consent. The Insight Study is registered at ClinicalTrials.gov (NCT00945633).

The main aim of the present study was to examine the associations between ocular volume, body size, and body composition. Specifically, we measured the volume of each eye with multi-slice MRI [3] and then related ocular volume to MRI-measured brain mass [11] and DXA-measured head mass, body mass, and body composition [19] using linear regression analysis methods. The allometric associations between each of these measures and body size (height) were established using a traditional allometric scaling approach as outlined in Statistical Methods. The inclusion of body composition measurements served a twofold purpose: the eye is a lean organ devoid of adipose tissue and might scale closer to fat-free body mass (FFM) or LST than to total body mass that includes fat mass; and the scaling relations for FFM and LST mass are well established [10,12,18] and served as an internal reference for the subjects evaluated in this report.

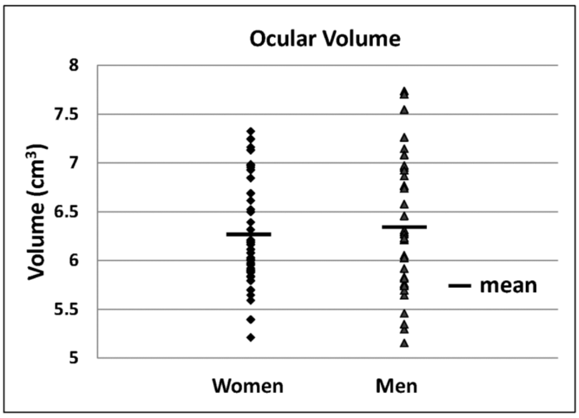

Figure 2: The mean ocular volume.

A concluding section of the paper includes a compilation of previous reports describing measurements of adult ocular volume from previous studies as found by PubMed, Web of Science, and Google Scholar searches and cross-referencing using the terms ocular and eyeball volume, mass, and size. Note that studies of ocular volume report size units in mass (g) or volume (cm^3). As noted in the Discussion, the density of the human eye is close to unity and we therefore do not attempt to reconcile study differences according to measurement units.

Participants

Those enrolled in the Insight Study were Caucasian, African American, or other ethnicities by self-report who were between the ages of 20 and 35 years, had a BMI<27.5 kg/m^2, and a fasting blood glucose<126 mg/dl. Each participant completed a clinical and physical examination to establish their health status prior to study enrollment. Subjects were excluded from the study if they had a history of diabetes, current or planned medication usage that might impact on future health status, a chronic or infectious disease, alcohol or illegal drug abuse, current pregnancy, or an eating disorder. Subjects were also excluded from the present report if their MRI scans were judged technically inadequate for ocular volume estimations due to motion artifacts. None of the subjects had a history of head or eye injuries or clinically significant eye diseases.

Measurements

Height was measured to the nearest 0.5 cm in each subject using a wall-mounted stadiometer (Holtain Limited, Crosswell, Crymych, UK) and screening weight was measured using a digital scale (GSE-450; GSE, Livonia, MI, USA) to the nearest 0.1 kg. Measurements were taken twice with a third reading obtained if the first two respective readings were >0.5 cm or >0.5 kg apart; results were averaged.

Dual-energy X-ray absorptiometry

Dual energy X-ray absorptiometry scans were performed using a Hologic QDR 4500A whole-body scanner with QDR software for Windows V11.1.2 (Hologic Corporation, Bedford, MA). The subject rested supine on the system platform wearing a hospital gown and with no attached metal during the 4-minute scan. Each scan was then evaluated for head mass, total body fat, FFM, bone mineral content (BMC), and LST. All statistical analyses were conducted for consistency with DXA-measured body mass.

Magnetic resonance imaging

Brain: Magnetic resonance imaging was performed using a 3.0T scanner (Excite HD System, General Electric, Milwaukee, WI). Subjects were placed supine on the scanner table with arms by their sides and a wedge cushion under the back of their knees.

Measure	Men	Women
Sample Size (race)	36 (31C, 4AA, 1O)	44 (33C, 8AA, 3O)
Age (yrs)	26.2 ± 4.0	27.0 ± 4.7
Weight (kg)	76.1 ± 7.9	61.0 ± 7.8**
Height (cm)	180.0 ± 7.1	165.2 ± 6.6**
BMI (kg/m^2)	23.6 ± 2.4	22.3 ± 2.1
%fat	17.3 ± 4.5	28.5 ± 5.2**
Head Mass (kg)	4.93 ± 0.31	4.37 ± 0.38**
Brain Mass (kg)	1.380 ± 0.100	1.235 ± 0.111*
Ocular Volume (cm^3) Right Left Mean	6.35 ± 0.68 6.34 ± 0.71 6.35 ± 0.69	6.25 ± 0.53 6.27 ± 0.55 6.26 ± 0.53
FFM (kg)	63.6 ± 6.7	43.8 ± 4.7**
LST (kg)	60.7 ± 6.5	41.5 ± 4.5**
BMC (kg)	2.85 ± 0.37	2.32 ± 0.32**
Fat Mass (kg)	11.5 ± 4.9	17.7 ± 4.9**
Ratios		
Brain/Head (%)	28.0 ± 1.8	28.4 ± 2.9
Eye/Brain (cm^3/kg)	4.63 ± 0.68	5.10 ± 0.54**
Eye/Head (%)↑	0.129 ± 0.016	0.144 ± 0.016**

Results are mean ± SD. AA: African American; BMC: Bone Mineral Content; BMI: Body Mass Index; C: Caucasian; FFM: Fat-Free Mass; LST: Lean Soft Tissue Mass; O: Other.
*p<0.05 and **<0.001 for men compared to women.
↑Assumes eye density of unity.

Table 1: Participants' characteristics.

The subject's head was placed in the 8 channel HD brain coil. After a localizer, a T2-weighted fast recovery fast spin echo (slice thickness of 1.7 mm with 0.3 mm inter-slice gap; TR 8600, TE 90, FOV 26, frequency 256, phase is 256, NEX (average) 2, scan time 7 min) scan was acquired with approximately 75 images created through the brain. The mean acquisition time, including positioning of the subject, was 45 minutes.

Brain volume was assessed from the T2-weighted axial series using AnalyzeTM software (AnalyzeDirect, Inc. Overland Park, KS) installed on a computer workstation. The region of interest was defined as all brain matter excluding the brainstem, cerebrospinal fluid, and the ventricles. Brain volume was calculated based on the number of pixels of the defined brain area measured in each image. Brain mass was calculated from volume as reported by Gallagher et al. [26]. The between-measurement coefficient of variation for brain volume on ten subjects was 0.6%.

Eye: The volume of each eye was assessed using the T2-weighted axial series. The images were imported into the AnalyzeTM software computer workstation and each eyeball evaluated by first locating the center or largest portion of the lens. The center image, four images above the center and four images below the center were then analyzed for a total of nine images. The stereology tool was used to overlay grid points on the eye only (Figure 1). The grid X/Y spacing was set to 2. The volume of each eye was measured separately and results are expressed in cm^3. The co-efficient of variation for left and right eye volumes were, respectively, 1.8% and 1.4%.

Statistical Methods

First, we examined the structural relations between ocular volume and body size-composition. The initial set of analyses applied linear regression analysis to develop eye-body size associations in the men and women. The over-arching aim of these analyses was to establish if and to what extent mean ocular volume correlates significantly with brain mass, head mass, body mass, and other body components. We began with analyses centered on the eye and then followed with related analyses of brain, head, and body mass. We examined associations in the whole group or only the large subset of Caucasian subjects (n=64 of 80 total) and there were no substantive differences in the results; we thus preserved study power by retaining the full sample (Table 1), and we additionally provide the findings solely for Caucasian subjects in Table 2. Descriptive results are provided in the text as the mean ± SD and for regression models as R2 and SEE.

In the next series of analyses we examined the stature scaling relations for ocular volume and the other anatomic components. The scaling relations were evaluated using the allometric model expressed as: $Y=\alpha X\beta$, where Y is the outcome (e.g., ocular volume), X is the predictor variable (i.e., height), β is the scaling exponent or "power", and α is the proportionality constant. The allometric models were developed with coefficients α and β estimated by least squares multiple linear regression analysis based on log-transformed data in the form of $\log eY=\log e\alpha+\beta\log eX+\varepsilon$, where ε is the error term. Body weight, ocular volume, and other body mass/composition measures were set as dependent variables and height, age, and adiposity (i.e., %fat by DXA) as independent variables in the regression models [19]. Log α and β values along with R2 and SEE values for the series of developed regression models are presented under results.

The statistical analyses were carried out using Stata 11 (StataCorp, Texas, USA) and Microsoft Excel 2010 (Microsoft Corp., Seattle, WA).

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Results

Participants

Two of the 82 InSight subjects were excluded from this report because they had eye motion artifacts precluding accurate ocular volume measurements. The selected sample included 80 subjects, 36 men and 44 women, with a group mean age of about 27 years (range, 20-35 yrs; Table 1). Of the men, 31 were Caucasian, 4 African American, and 1 designated as other. Of the women, 33 were Caucasian, 8 African American, and 3 designated as other. The group as a whole was normal weight, with a mean body mass index of about 23 kg/m^2 (range, 18.4-27.4 kg/m^2).

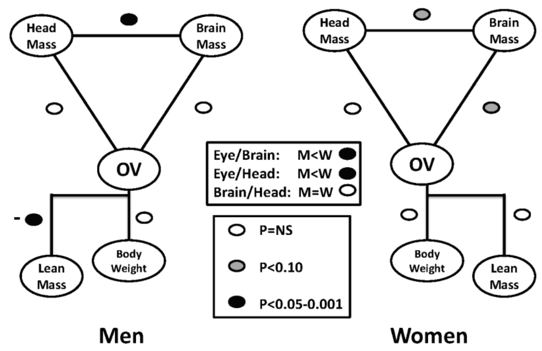

Figure 3: The relations between ocular volumes, brain mass, head mass, body size, and body composition

Structural relations

Eyes: The right and left ocular volumes were highly correlated with each other in both the men (R2, 0.91; SEE, 0.22 cm^3; p<0.001; Δ, 0.02 ± 0.21 cm^3) and women (R2, 0.89; SEE, 0.18 cm^3; p<0.001; Δ, 0.02 ± 0.18 cm^3) with no significant volume difference between the two eyes within either sex group (Table 1).

The mean ocular volume was larger in men (6.35 ± 0.69 cm^3; range 5.15-7.74 cm^3) than in women (6.26 ± 0.53 cm^3; 5.21-7.32 cm^3), although the difference was not statistically significant (Figure 2). The relations between ocular volumes, brain mass, head mass, body size, and body composition as presented in the next series of analyses are summarized in Figure 3.

Mean ocular volume was non-significantly (p>0.05) correlated with age, height, weight, FFM, LST, BMC, or fat mass in the women. The mean ocular volume in men was significantly correlated (p<0.05) with age (positive slope), FFM (negative slope), and LST (negative slope) but not with height, weight, BMC, or fat mass. Both age and lean mass (FFM and LST) in men remained significant predictors of mean ocular volume in a multiple regression model that included fat mass and height, neither of which were significant covariates. Ocular volume in men remained non-significantly larger from women after adjusting for age, fat mass, and lean mass components.

Brain: Men had a significantly larger brain mass (1.380 ± 0.100 kg) than women (1.235 ± 0.1611 kg; p<0.001). Brain mass in the men was significantly (p<0.05) correlated with body weight, FFM, LST, and BMC but not with age, fat mass (p=0.10), or height. Brain mass was not significantly correlated with age, height, body weight, fat, FFM, LST, or BMC in the women. The significant sex difference in brain mass remained present (~0.1 kg) after adjusting for age, fat mass, and FFM in multiple regression models.

There was a borderline significant correlation between brain mass and mean ocular volume in the women (R2, 0.09; p=0.076) but not the men (p=NS). Relative to brain mass, there was 4.63 ± 0.68 cm^3 and 5.10 ± 0.54 cm^3 ocular volume per kg in the men and women, respectively (p<0.001) (Table 1).

Brain mass and head mass were significantly correlated in the men (R2, 0.31; SEE, 0.06 kg; p<0.001) while a borderline significant correlation between the two was present in the women (R2, 0.08; SEE, 0.09 kg; p=0.066).

Measure	Men	Women
Sample Size (race)	31	33
Age (yrs)	26.3 ± 4.2	27.0 ± 4.7
Weight (kg)	75.9 ± 7.7	61.0 ± 8.1**
Height (cm)	179.6 ± 7.1	165.1 ± 6.9**
BMI (kg/m^2)	23.8 ± 2.3	22.3 ± 2.1*
%fat	17.1 ± 4.4	28.6 ± 5.4**
Head Mass (kg)	4.89 ± 0.29	4.30 ± 0.34**
Brain Mass (kg)	1.39 ± 0.11	1.26 ± 0.11**
Ocular Volume (cm^3) Right Left Mean	6.37 ± 0.65 6.35 ± 0.67 6.36 ± 0.65	6.30 ± 0.53 6.30 ± 0.55 6.30 ± 0.53
FFM (kg)	63.4 ± 6.8	43.4 ± 4.9**
LST (kg)	60.6 ± 6.5	41.1 ± 4.7**
BMC (kg)	2.82 ± 0.38	2.30 ± 0.34**
Fat Mass (kg)	13.1 ± 0.37	17.7 ± 5.0**
Ratios		
Brain/Head (%)	28.4 ± 2.0	29.4 ± 2.1
Eye/Brain (cm^3/kg)	4.62 ± 0.67	5.03 ± 0.51*
Eye/Head (%)↑	0.131 ± 0.015	0.147 ± 0.013**

Results are mean ± SD. BMC: Bone Mineral Content; BMI: Body Mass Index; FFM: Fat-Free Mass; LST: Lean Soft Tissue Mass.
*p<0.05 and **<0.001 for men compared to women.
↑Assumes eye density of unity.

Table 2: Caucasian participant characteristics.

Head: Men had a significantly larger head mass (4.93 ± 0.31 kg) than women (4.37 ± 0.38 kg, p<0.001) while the fractional contribution of head mass to body mass was significantly smaller in men (6.53 ± 0.67%) than in women (7.23 ± 0.77%; p<0.001). The percentage contribution of brain mass to head mass was almost identical in the men (28.0 ± 2.9%) and women (28.4 ± 1.8%).

Head mass and mean ocular volume was not significantly correlated in the men or women. The mean ocular volume (assuming a density of unity) was a significantly larger (p<0.001) percentage of head mass in the women (0.144 ± 0.016 %) compared to the men (0.129 ± 0.016 %; Table 1).

Allometric analyses

Body weight, FFM, LST, and BMC scaled to height, after adjusting for age and adiposity, with powers of 1.57-1.80 in the men and 1.66-2.60 in the women (Figure 4). Brain mass scaled to height with a power of 0.81 in the men and was non-significantly correlated with height in the women. Mean ocular volume scaled negatively to height in the men with borderline significance (power, -0.86 ± 0.42; p=0.051 after adjusting for age) and was not significantly correlated with height in the women. Head mass scaled with respective powers of 0.42 and 0.52 in the men and women, although the allometric models were borderline significant (p=0.10 and 0.08).

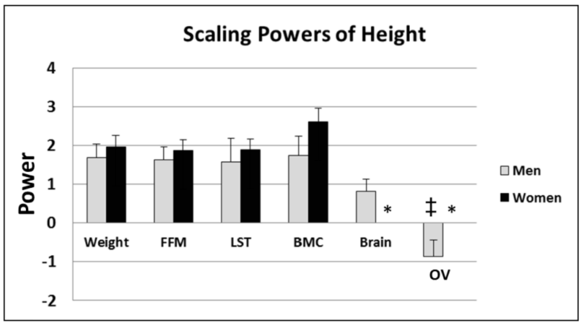

Figure 4: Body weight, FFM, LST, and BMC scaled to height.

Discussion

In the current study we aimed to fill a gap associated with how ocular volume relates to body size and composition across healthy young men and women. This information is useful in the context of developing a wide range of biological models of contemporary interest. We have reported similar allometric body size associations for larger organs and tissues in earlier reports [10,17,19].

Our findings suggest that mean ocular volume has very limited associations with body mass as a whole, the brain, head, other major body components, and with stature. There was a small non-significant sex difference in mean ocular volume (~0.1 cm^3), with absolute volume in men larger than in women. Ocular volumes were significantly larger relative to brain and head mass in the women.

Ocular volume estimates

The focus of most ophthalmologic research is on the eye as an instrument of vision and in that context pathological changes within the eyes and related structures. Hence, there are a number of studies that have examined specific ocular dimensions and vision components in relation to body size such as the cornea and retina [27,28]. A second related series of previous studies map out the development of the human eye in relation to body growth from birth onward [23,29-35]. Very few well-controlled studies have evaluated ocular volume as a whole and its relationship to body size and composition in healthy adults. Those that have found variable ocular volume estimates that are likely related to the employed measurement methods.

A summary of previous reports on ocular volume and mass is presented in Table 3 with a focus on young adult age groups as reported in the current study. In the discussion that follows we assume that ocular volume and mass differ by only several percent as we measured a human eye density of (X ± SD) 1.022 ± 0.029 g/cm^3 in 8 unembalmed human cadavers (Table 4).

Scammon and Armstrong's [23] review of previous autopsy studies reports an ocular mass of 7.18 grams in 16 adults and is cited as 14.4 g for both eyes in the widely used Reference Man book [1]. Brock's 1932 review gave a mean autopsy adult ocular mass of 7.5 g, reported as 15 g for both eyes in Reference Man [1]. Todd et al. [2] reported the first comprehensive study of ocular mass with aims similar to those of the current report. The authors used autopsy material and established optimum dissection and hydration procedures in a series of Caucasian and African American males and females from birth to adults. In the small sample (n=49) within the age range evaluated in the current study (~20-39 yrs) Caucasians tended to have smaller ocular mass (~7 g) than African Americans (~8 g) and absolute ocular mass was similar in men and women while "relative" volumes were larger in the women. Limited associations between cranial capacity, a measure of brain volume, and ocular mass were observed in the Caucasian male adult sample (r=-0.0664 ± 0.0849; p=NS); these evaluations were thus not pursued in the other groups. We found similar overall ocular mass results (~7 g/eye) to those by Todd et al. in the Belgian Cadaver Study [30] in a small previously unpublished sample of Caucasian men (n=11) and women (n=11) (Table 4). Thaller [24] measured ocular volume by water displacement post-surgery in 10 normal enucleated eyes and found a mean value of 8.15 g that included a small portion of the optic nerve.

Modern imaging methods, MRI, CT, and ultrasound are now the mainstay for measuring ocular volume *in vivo* (Table 3). Our estimates of mean ocular volume as measured by MRI (~6.5 cm^3) are very similar to those reported for MRI by Chau et al. [21] in young Korean adults (17 women, 16 men; left eye, ~6.7 cm^3), Lee et al. [31] in young Korean adults (32 men, 39 women; mean, ~6.6 cm^3) [31], and Pearce and Bridge [6] (mean in combined men and women, ~6-7 cm^3). Park et al. [32] found much larger ocular volumes with MRI in Korean adults, 9.7 cm^3 for men and 9.2 cm^3 for women.

Hahn and Chu [33] evaluated ocular volumes in 74 males and females of unspecified ethnicity with computed tomography (CT) and reported values in adults approaching those of the early autopsy findings, in the range of 8-10 cm3 [33]. Acer et al. [20] evaluated ocular volume using CT and stereological methods in 36 Turkish adults of unspecified ethnicity and also found mean values in the range of 7-8 cm^3. Igbinedion and Ogbeide [34], however, found substantially smaller ocular volumes measured by CT (~5.3 cm^3) in 200 African males and females distributed across the lifespan. Ogbeide and Omoti [35] evaluated ocular volume in Nigerian men and women with B-mode ultrasound and found mean values between 5.4 cm^3 and 5.8 cm^3. The variation in ocular volume and mass across studies can likely, in part, be attributed to sample characteristics such as race and age along with differences between measurement methods such as those reported by Chau et al. [22] and Tian et al. [36].

Author	N	Age (yrs)	Methods (units)	Ocular Volume/Mass		Comments
				Men	Women	
Todd et al. [2]	150	Mean 37-64	Autopsy (g)	C 7.85 ± 0.05 AA 8.51 ± 0.10	C 7.29 ± 0.10 AA 7.95 ± 0.11	Overall, larger volumes in men and African Americans
Scammon and Armstrong [23]	16	Not specified	Autopsy (g)	7.2		No sex or race specified
Brock	Adults	Not specified	Autopsy (g)	7.5		No sex or race specified
Clarys et al. [30]	22	Mean 70-80	Autopsy (g)	7.12 ± 1.10	6.81 ± 1.40	Details in Table 2
Thaller et al. [24]	10	Not specified	Enucleated Eye (cm^3)	8.15		Volume of eyes judged "normal" relative to a healthy eye
Acer et al. [20]	36 15 M 21 W	M: 41.5±3.1 W: 39.4±5.3	CT Cavalieri (cm^3): Point Counting Planimetry	7.48 ± 0.80 7.49 ± 0.79	7.21 ± 0.84 7.06 ± 0.85	Race not specified. Sex differences non-significant.
Hahn and Chu [33]	8 26	18-30 30-50	CT (cm^3)	9.69 ± 1.66 8.81 ± 0.70	10.13a 9.79 ± 0.70	Data presented here only for adults within current study age range.
Ingbinedion and Ogbedie [34]	56	21-30 31-40	CT (cm^3)	R 5.56 L 5.64 R 5.38 L 5.47	R 5.20 L 5.18 R 5.42 L 5.58	Overall, larger volumes in males but differences from females non-significant. Nigerian Sample.
Ibinaiye et al. [3]	100 total; unspecified N between ages 21-40 yrs	21-30 31-40	MRI (cm^3)	R 7.21 L 7.25 R 7.34 L 7.40	R 7.05 L 6.73 R 7.21 L 7.01	Overall, larger volumes in males but differences from females non-significant. Nigerian Sample.
Chau et al. [21], Chau et al. [22]	33 16 M 17 W	19-42, mean 21	MRI of L eye (cm^3)	6.55 ± 0.94	6.84 ± 0.88	Race not specified. Ametropia present in all subjects.
Park et al. [32]	121 66 M 55 W	25-50	MRI of both eyes (cm^3)	19.3 ± 0.7	18.4 ± 2.7	Volume of both eyes in Korean adults; 6 mm slice interval.
Ogbeide and Omoti [35]	200 total; 29 M and W 10 M and W	20-29 30-39	B-mode ultrasound of both eyes (cm^3)	R 5.73 ± 0.29 L 5.42 ± 0.14 R 5.65 ± 0.27 L 5.80 ± 0.32		Combined Nigerian men and women; no significant sex differences in study as a whole.

a, n=1. ‡Subjects without myopia. Results are X ± SD. Abbreviations: AA: African American; C: Caucasian; CT: Computed Tomography; L: Left; M: Men; MRI: Magnetic Resonance Imaging; R: Right; OV: Ocular Volume; W; Women.

Table 3: Relevant previous ocular volume or dimension studies.

Sex differences

Men in the current study were taller and weighed about 20% more than the women. By contrast, eye volumes only differed by ~0.1 cm^3 or 1-2%. We could find no sexual dimorphism in ocular volume even after adjusting for body size and composition. As in our study, Chau et al. [21] found a small non-significant ocular volume difference between men and women (~0.3 cm^3) while a slightly larger magnitude difference reached significance in the sample of Lee et al. [31] (~0.5 cm^3); sex groups were not reported separately by Pearce and Bridge [6]. Hahn and Chu [33] observed a larger eye volume in males than females across the lifespan (~0.5 cm^3), although the between-sex differences were inconsistent in adults. Igbinedion and Ogbeide [34] found that males had a slightly larger ocular volume than females (0.1 cm3 or 2%; p=NS). In a different sample, Ogbeide and Omoti [35] also found a non-significant male-female difference (~0.2 cm^3) in ocular volume. Ibinaiye et al. [3] found a small (~0.2 cm^3) sex difference in ocular volume that was non-significant (p=0.06). Acer et al. [20] in their stereological-CT study found that with planimetry mean (±SD) values of men and women were 7.49 ± 0.79 and 7.06 ± 0.85 cm^3 (Δ 0.43 cm^3) and by the point-counting method 7.48 ± 0.85 and 7.21 ± 0.84 cm3 (Δ 0.27 cm3), respectively (both, p=NS). In one of the earliest studies, Todd et al. [2] reported a larger post-mortem ocular mass in men than in women (~0.5 cm^3), although subjects were not well matched for age. Men in the Belgian Cadaver Study had a larger ocular mass than women (~0.3 cm^3 (Table 4; p=NS). Ogbeide and Omoti [35] found non-significant ocular volume differences between Nigerian men and women with B-mode ultrasound. In an extensive literature review, Augusteyn [29] reported that humans, rhesus monkeys, baboons, and a wide range of other animals also lack a significant sex difference in lens size. In a more recent report, Augusteyn et al. [37] found that human male and female eyes from people of the same age have equivalent globe and cornea dimension.

The current study findings combined with these collective observations suggest that ocular volume in men is equivalent or slightly larger to that in women, but that the reported size differences are not proportional to sex differences in body, head, brain, or LST mass.

Body composition associations

The eye sits within the orbit and connects through the optic nerve to the visual cortical areas of the brain [38]. These structures are all relatively small, the orbit approximately 20-30 cm3 [6,21] and the visual cortical grey matter areas collectively about 30-50 cm3 [6] compared to the mean ocular volume of 6-8 cm3. Even so, ocular volume does not consistently correlate with orbital volume [21] and when it does the R2s tend to be fairly low, in the range of 0.1-0.2 [6]. Likewise, correlations between ocular volume and brain visual cortical areas tend to be low with R2 also in the range of 0.1-0.2, even when men and women are pooled in these analyses [6]. Todd et al. [2] found no correlation between ocular mass measured by cadaver dissection and cranial capacity. Our finding that ocular volume was not significantly correlated with the much larger head (~4-5 kg) and brain mass (~1.2-1.4 kg) is consistent with these earlier observations. Ocular volume relative to head and brain mass in our study was significantly larger in women than observed in men.

Eyes, brain, and head each have different growth trajectories reaching peak size within the first year of life, during adolescence, and early in adulthood, respectively [37]. Factors controlling the growth of these structures and their ultimate mass are thus likely different and may explain the absent or weak associations between them observed in the current study.

Allometric relations

The current study confirmed that major lean body components scale to height with powers centering widely around 2 [12,17,39]. Similarly, we found that as in other studies, brain and head mass scale to height with powers typically less than about 1 or non-significantly [10,16]. Thus taller subjects have a relatively smaller brain and head mass than their shorter counterparts. We found that ocular volume scaled weakly or non-significantly to height in the men and women, respectively. Ocular volume scales negatively to body mass across primates with a power of 0.18 [15]. Large primates thus have relatively smaller eyes than their lower weight counterparts. Neanderthals appeared to have larger orbital volumes and larger proportions of their brains devoted to vision than do humans [40].

Eyeball dimension studies

While the current study focus was on ocular volume relations, several studies have examined closely related eyeball diameters. One widely cited study [41] suggests that eyeball dimensions in adults are largely independent of sex and age. The authors examined the CT-measured transverse, sagittal, and axial eyeball diameters on 250 Middle-Eastern healthy adults and found no significant differences between men and women or across the age span of 18 to 93 years. By contrast, small but statistically significant differences in A mode ultrasound-measured eyeball dimensions were detected across men and women and in relation to stature in a large sample (n=951) of Chinese subjects living in Singapore who ranged in age from 40 to 81 years and in height from 1.37 to 1.83 m [27,28]. Similar magnitude eyeball dimension differences were observed across the full stature range. Assuming the adult eye is approximately spherical, the sex differences in eyeball dimensions and those observed across the full range of height would translate too roughly <0.5-1 cm^3 differences in ocular volumes.

Study limitations

The current study had several limitations that could potentially be overcome in future studies. First, our sample size was relatively small (n=80) and we thus lacked power to detect small sex, body size, and body composition differences and effects. Most of the other studies examining ocular volumes across the age span similarly had small samples and an opportunity thus exists to resolve prevailing ambiguities (e.g., sex, age, or race differences in ocular volume) with larger subject groups. Relevant power calculations for testing hypothesis in future studies can be derived from the present study results and reviewed literature. Second, while our sample was very carefully selected to ensure good health and the absence of medical conditions, we did not conduct a comprehensive ophthalmic evaluation that might have provided additional subject quantitative exploratory data related to subtle differences in visual acuity. Lastly, our evaluation included measurement of total brain and head mass although we did not probe further as in some other studies to specific skull or brain regions [6].

Measure	Men	Women
Sample Size	11	11
Age (yrs)	72.8 ± 7.8	79.5 ± 8.0
Weight (kg)	65.2 ± 12.6	63.2 ± 9.1*
Height (cm)	167.6 ± 8.4	158.3 ± 7.4
BMI (kg/m^2)	23.1 ± 3.3	25.3 ± 4.0
Brain Mass (kg)	1.351 ± 0.177	1.162 ± 0.136*
Ocular Mass (g)	7.12 ± 1.10	6.81 ± 1.40
Eye/Brain (cc/kg)	5.29 ± 0.75	5.93 ± 1.28

Results are mean ± SD. BMI: Body Mass Index
*<0.01 for men compared to women.
Subjects were those reported by Clarys et al. who had both measured eye and brain mass results. Measured density of unembalmed eye, n=8, 1.022 ± 0.029 g/cm3.

Table 4: Belgian Cadaver study results.

Conclusions

The current study aimed to fill a knowledge gap on how human ocular volume relates to body size and composition. Our efforts were motivated by the need for comprehensive biological model development information beyond that of the now well-studied large and easily measured organs and tissues [9,11,19]. Unlike most of the large organs and tissue components, we found in a carefully-evaluated sample of young healthy adults that human ocular volume has minimal associations with body size and composition measures and that little or no sexual dimorphism exists in eye size. As a small anatomic body unit, the adult human eye appears to function within relatively narrow dimensional constraints.

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Author Contributions

SBH, MCG, and DT analyzed the data and drafted the manuscript. SBH, KM, EC, JPC, GJ, and AS designed the study, and directed implementation and data collection. KM, EC, JPC, and AS collected the data, and SBH provided necessary logistical support. SBH, MCG, DT, KM, GJ, EC, JPC, and AS edited the manuscript for intellectual content and provided critical comments on the manuscript.

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