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Evaluation of Age-Related Changes in Human Lens Stiffness Through a Novel Non-Invasive Method Using Shear Wave Ultrasound Elastography

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ABSTRACT

Purpose: Presbyopia is an age-related condition characterized by diminished near-vision, primarily due to changes in the lens' adaptive capacity. Shear Wave Ultrasound Elastography (SWE) offers a novel/noninvasive method to measure lens stiffness and could potentially enhance our understanding of presbyopia's development. We aimed to use SWE to assess the elasticity of the human lens and explore the correlation between lens flexibility, age, presbyopia, and accommodation capacity.

Methods: A cross-sectional analysis was conducted with 84 participants (mean age = 39.61 ± 9.60) from a government hospital in Serdang, Selangor, Malaysia. Eligibility was confirmed through refractive error and visual acuity tests. Selected participants underwent SWE scanning, and measurements of accommodation and presbyopia were taken. Statistical analysis included descriptive summaries and Pearson correlation coefficients to examine relationships between lens elasticity age, presbyopia, and amplitude of accommodation.

Results: The analysis demonstrated a weak correlation between lens elasticity and age in nonpresbyopic group (r=0.289) while positive strong correlation in presbyopic group (r=0.674). A strong positive correlation was observed between lens elasticity and presbyopia in presbyopic group (r=0.612). Moreover, there was a negative correlation with accommodation in both groups, (r=-0.358) for nonpresbyopic and (r=-0.493) presbyopic group.

Conclusions: While lens elasticity diminishes with age, changes in ocular biomechanical properties impact lens function, particularly affecting near vision. Importantly, SWE is found to be an effective tool for assessing age-related changes in lens elasticity and presbyopia across various age groups, highlighting its potential for broader clinical application in diagnosing and understanding presbyopia.

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Introduction

The lens of the human eye has a precise asymmetric biconvex shape in which the anterior surface has less curvature than the posterior, and the equator refers to the meeting point between the front and back surfaces. At birth, the human lens weighs around 65 mg, increasing to about 160 mg and 250 mg at the age of 10 and 90, respectively.[1] Proteins account for approximately 60% of the increased mass of the lens, which is exceptionally incomparable to any other tissue.[1]

The human eye also consists of four refractive index components, which include the cornea, lens, aqueous, and vitreous humor. Massive contents of soluble proteins are pivotal in the lens's refractive index, classified as crystallins.[2] The protein content supplies the lens with its elastic characteristics, which aids in changing its shape through ciliary muscle contraction—a smooth muscle that alters the curvature of the eye lens *via* decreasing the anterior zonules' tension.[3] Overall, the concept for alterations of processes is known as accommodation.[3–5]

Nevertheless, the accommodative amplitude steadily diminishes with age, from approximately 15D in childhood and adolescence to 1D before the age of 60,[6] a condition called presbyopia that causes difficulty with near eyesight and close tasks. Most individuals experience the beginning of presbyopia between the ages of 40 and 45.[7] This phenomena

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occur due to an increase in free water content and a reduction in bound water content, with the natural lens becoming harden and losing its viscoelasticity.[8,9] The diagnosis and management of these eye defects can be enhanced by evaluating the biochemical properties of ocular tissues.

Several measuring modalities are used to determine the lens elasticity degree, such as Brillouin microscopy imaging technique, Magnetic Resonance Imaging (MRI), and Optical coherence tomography. Brillouin scattering is generated by acoustic phonons, followed by characterizing the acoustic properties of materials at GHz and measuring the longitudinally elastic properties of lenses.[10,11] The MRI approach uses the lens refractive index and relaxation period dependency on the local protein concentration by measuring the refractive index and associated values R2 (1/T2) for portions of lens homogenates with varying protein contents. These features make it possible to identify changes in the crystalline lens and ciliary body with accommodation and age, thereby facilitating dimension measurement without any need for optical property assumptions.[12] Optical coherence tomography quantifies the correlation between visual changes in an accommodating eye and the structural modification of its crystalline lens, a comprehensive scan-depth anterior segment technique employing acoustic radiation force stimulation to evaluate the lens and corneal stiffness concurrently.[13,14]

However, the aforementioned modalities for measuring lens elasticity have important limitations. For instance, due to weak scattering efficiency in the Brillouin microscopy imaging technique, a longer integration time and high illumination power are required. The scattering processes can also damage live cells and tissues, especially as the superimposed light is absorbed.[15,16] Meanwhile, MRI is not cost-effective for routine use and obtaining a high-resolution MRI data is usually time-consuming, which is a major limitation *in vivo* imaging.[17]

Elastography was introduced in 1980 as a noninvasive method for evaluating the rheological (the scientific study of measuring deformation) characteristics of human soft tissues using ultrasound.[18] There are four main types of elastography techniques: transient, strain, acoustic radiation force impulse imaging, and shear wave elastography (SWE). In clinical scanners, the strain elastography (SE) and SWE are the primary approaches. The SWE is a new generation real-time quantitative elasticity imaging technique that has been successfully used in studies involving biometric measurements of thyroid, liver and musculoskeletal tissues.[19] It usually generates shear waves to represent the quantitative stiffness values in kilopascals (kPa).[17] Due to its several intrinsic benefits, such as wide availability at the bedside, and cheap cost, ultrasound-based techniques have continued to gain considerable interest.[20,21] SWE can efficiently detect and photograph the elasticity of tiny lesions with millimeter accuracy and real-time imaging capability.[22]

There are currently a variety of presbyopia therapies ranging from noninvasive methods to a series of surgical procedures. Many years have passed since the introduction of nonsurgical optical methods for treating by spectacles lenses or contact lenses that provide the highest clarity of vision in the majority of cases.[23–25] Newer innovative imaging methods are being combined with a quantitative analysis method known as "SWE." This combination includes the use of both "pSWE" and the more modern "2DSWE".[26] Nevertheless, there is limited information on the use of SWE in assessing presbyopia among individuals of different age groups.

The motivation of this study was to investigate an *in vivo* technique, SWE, for assessing the mechanical properties of the lens in a noninvasive manner among individuals of diverse age groups, as well as assessing the strength of association (correlation) between age and each of the flexibility of the lens, degree of accommodation, presbyopia. The findings are expected to depict the suitability of using SWE in assessing these optical parameters and presbyopia in human subjects, thereby improving our understanding on the pathogenesis of lens disorders and promoting the development of novel treatments.

We hypothesized that the degree of lens elasticity decreases in presbyopic individuals, which reduces the lens's ability to change its shape, thereby impairing the production of different power degrees necessary for near vision. Additionally, we hypothesized that accommodation is related to the biomedical properties of lens tissue. This lead us to pose the following research questions: Does lens elasticity play a role in accommodation in presbyopia? Is ultrasound elastography an accurate device for measuring lens elasticity? How does refractive error affect the biomedical properties of lens tissue?

Materials and methods

Study design

A cross-sectional study of individuals aged 19 to 65 years old visiting the consulting clinic at the ophthalmology and radiology department of Hospital Sultan Abdul Aziz Shah, University Putra Malaysia, Serdang, Selangor was conducted from April 2022 to August 2022.

Inclusion and exclusion criteria

Eligible study participants were required to have the best possible corrected visual acuity of ≥6/9, and ready to provide informed and written consent. A single eye with the clearest vision was selected coupled with monocular assessment to identify the best visual acuity. Exclusion criteria included individuals with refractive defect, presenting with corrective eye surgery, amblyopia, previous record of eye surgery, trauma to the lens, exophthalmos, currently on medication that heightens the risk of water retention, and patients having cataracts, diabetes, and eye diseases affecting the eye's axis such as advanced stage of glaucoma, and total optic-nerve cupping with a lower field of vision. Participants were recruited using convenience sampling method.

Sample size and sampling method

The use of G-Power is recommended for the quantitative determination of sample size. Based on a low positive correlation coefficient of 0.15 reported in a previous study,[27] statistical power of 80%, and precision error of 0.05, a minimum sample of 84 participants was estimated.

Ethical clearance

This study was approved by the University of Putra Malaysia's Ethics Committee for Research Involving Human Subjects (JKEUPM) with the Reference Number: JKEUPM-2022-052.

The characteristics of the ultrasound shear wave elastography system

The axial and lateral resolution depend on the transducer frequency and system capabilities. For the Canon Aplio i800 with the i18LX5 transducer, the axial resolution is typically in the range of 50-100 microns, while the lateral resolution depends on beam focusing and depth but is usually higher than axial resolution (approximately 200-300 microns). The FOV for the i18LX5 transducer is typically around 38 mm in width, but this depends on the imaging depth and the specific settings used during acquisition. Shear waves in this study were generated using Acoustic Radiation Force Impulse (ARFI) technology, which is a standard method for SWE implementation in the Canon Aplio i800 system. The time resolution in SWE depends on the frame rate and the time interval used to track shear wave propagation. For the Canon Aplio i800, the time resolution is typically in the range of a few milliseconds (often 2–10 ms per frame, depending on the acquisition parameters and depth).

Safety considerations of ARFI

Unlike conventional B-mode ultrasound, ARFI imaging requires higher mechanical index (MI) settings to generate tissue displacement. In this study, we implemented comprehensive safety measures to mitigate any potential risk associated with the higher acoustic output. The MI used during ARFI acquisition was 0.6, which, although above the ophthalmic safety threshold of 0.23, remains well within the general diagnostic ultrasound limit of 1.9 set by the U.S. Food and Drug Administration (FDA). Importantly, this value is permitted under the FDA's Track 3 designation for elastography, which allows the use of elevated acoustic intensities under controlled and regulated conditions. ARFI imaging was performed using brief excitation pulses (<1 ms) and a temporal resolution of 2–10 milliseconds per frame, thereby limiting thermal and mechanical exposure to ocular tissues. Shear wave speed in the crystalline lens ranged from 1.18 to 2.42 m/s, with a mean of 1.84 ± 0.33 m/s at a depth of 0.7 cm—values that are consistent with physiological norms. All imaging procedures strictly followed the ALARA (As Low As Reasonably Achievable) principle and adhered to the safety guidelines specified by the manufacturer. Furthermore, supporting clinical evidence, such as the study by Palmeri et al. (2011),[28] has shown no significant tissue heating or adverse bioeffects when MI remains below 1.9. No participants in this study experienced discomfort or adverse effects during or following the imaging sessions, indicating that the procedure was well-tolerated and safely executed.

The crystalline lens shear wave propagation via ARF

The crystalline lens wave propagation regarding, the Canon Aplio i800 ultrasound system with the i18LX5 transducer was used to generate shear waves *via* ARFI. The primary waves of interest in this study were shear waves, as these are the basis for estimating tissue stiffness in SWE.

The wavelength of the generated shear waves depends on the shear wave speed and the viscoelastic properties of the crystalline lens. Based on previous literature and our findings, the estimated shear wave speed in the lens tissue falls within the range of 1.18–2.42 m/s, with mean 1.84 m/s and SD 0.33 m/s, corresponding to a shear wavelength of approximately 0.1022 m average. Regarding the conversion of shear wave speed into Young's modulus, we applied the standard elasticity equation for isotropic materials:

The shear wave elastography employed (SWE), where the primary waves of interest were shear waves, generated *via* ARFI. The objective was to estimate tissue stiffness by measuring the propagation speed of these shear waves. The shear wave speed in the crystalline lens has been reported in previous studies, primarily in animal models. For example, in *ex vivo* bovine lenses, shear wave speeds were estimated to range from 1.44 ± 0.27 m/s to 2.03 ± 0.46 m/s.[29] In porcine lenses, shear wave speeds varied from 1.19 ± 0.25 m/s (without capsule) to 2.55 ± 0.23 m/s (with capsule intact) (Frontiers in Bioengineering and Biotechnology, 2023). These values suggest that shear waves propagate at a relatively low speed in the lens due to its viscoelastic properties.

Using the relationship $\lambda = v_s/f$, where v_s is the shear wave speed and f is the excitation frequency (assumed ~1000 Hz in previous SWE studies), the corresponding shear wavelengths would be approximately 1.44 mm to 2.55 mm. However, we acknowledge that the precise wavelength in human lenses may differ due to variations in age, lens stiffness, and other biological factors.

Regarding the conversion of shear wave speed into Young's modulus, the standard elasticity equation applied for isotropic materials:

$$E = 3\rho v_s^2 \left(1 + 2\nu\right)$$

where E is the Young's modulus, ρ is the tissue density, v_s is the shear wave speed, and ν is the Poisson's ratio. While the crystalline lens is known to exhibit viscoelastic properties, the assumption of an approximately isotropic behavior was used for the purposes of this study.

SCANNING protocol in human eye

The subject was advised to lie down on the inspection bed in the spine posture and was given instructions to look in a straight line prior having both eyes closed (the eyelid closed

Figure 1. The technique of holding the prob.

to ensure patient comfort, reduce involuntary eye movement, and prevent potential corneal irritation from direct ultrasound exposure). We performed SWE on *in vivo* human eyes using a linear i18LX5 probe with the Canon Aplio i800 ultrasound system, using ultrasound gel as the acoustic interface used on the probe's surface. The transducer was then positioned on the eyelid, beam was directed perpendicularly to the anterior lens surface and ensuring consistency across subjects; to prevent the probe wire from coming into contact with the subject's face, we found that twisting it once in our wrist is the most effective gripping technique. After positioning gently, the probe on the over the closed eyelid, we rest our pinky finger on the subject's nose and use our other fingers to hold the probe steady so that we can maintain control over it during the scanning process and optimize transmission while minimizing mechanical compression of the eyeball. Figure 1 shows the technic probe holding.

The MI used in this study was 0.06 which complies with ophthalmic safety guidelines (<0.23 per FDA standards). The transducer was chosen for its high axial resolution (~50–100 microns) and compatibility with superficial tissue imaging. Temporal resolution (2–10 ms per frame) was factored into measurement accuracy. While this is a novel application, preliminary validation and safety considerations were undertaken, and no adverse effects were reported. Future work will include direct validation against alternative ophthalmic elasticity measurement techniques.

Study outcomes

Assessment of refractive error, presbyopia and amplitude of accommodation

A trained assessor conducted several eye examinations on each participant before using the HUVITS® auto-refractometer to determine the presence or absence of refractive errors. Assessment of visual acuity was carried out by using a computerized display screen as described in a previous study,[30] including the trial case's lens corrected any vision anomalies. Subsequently, the outcomes were rated as follows: 6/6, 6/9, 6/12, 6/18, 6/24, 6/36, and 6/60. For participants having vision problems, lens degrees were added to the frame to determine the visual acuity. Each participant's assisted and unaided visual acuity results were documented. The lens elasticity was used as a guide for the presbyopia and accommodation assessments as described in previous studies.[30,31]

Presbyopia was assessed by using a near-distance graph check chart, which was held by the subjects in the presbyopia group. A convex lens was added to the frame, and the subjects were asked about their ability to read the line. The degree of presbyopia corresponds to the lens power that was added. While in amplitude of accommodation assessment, the push-up technique was employed to perform the calculation using the RAF ruler. The ruler was held by its handle, and the V-shaped check rest was carefully positioned on the middle of the nose, close to the orbit's edge. The subject was instructed to focus on the N8 line, while the marker was brought to a distance of 40 centimeters for direct viewing.

Further examinations were performed on the eye with the best vision. Upon identifying the clearest eye.

Ultrasound SCANNING measurement using shear wave elastography

The radiological measurements were equally conducted using the Canon (aplio i800) instrument to measure the lens elasticity.[31] All participants were subjected to a comprehensive ophthalmological examination as described in the previous sections before ultrasound scanning measurement. The i-series Aplio devices, an advanced SWE method for quantitative analysis as described by Kawahara et al. on 2020,[26] were utilized and outfitted with the "i18LX5" transducer for this research. This transducer is linear and ultra-wideband, possessing identical bandwidth to two standard transducers. Furthermore, it provides unparalleled clarity in imaging while upholding maximum sensitivity in nearby and far-off areas (Canon Medical System, Malaysia).

To standardize accommodation conditions, participants were instructed to fixate on a distant target (~6 meters away, point on the celling) in a dimly lit environment. Reducing accommodation-induced changes in lens stiffness, this ensured that the ciliary muscle remained in a relaxed state, keeping the crystalline lens in its unaccommodated configuration, and then asked the participants to closed the eye, as closing the eye will remain in unaccommodated because of the absence of a the stimulating body.

The electrograms are displayed by the machine software in the form of an overlay in two modes (horizontal/vertical) simultaneously with grayscale images (Figure 1). The operator adjusted the sonography window to the region of interest (ROI). An automated adjustable rectangular electronic box was placed on the elastogram screen, which helped in displaying the tissue stiffness in real-time. This integrated SWE software permits the placement of circular ROIs of different diameters within the elastography window and displays the shear modulus data (measured in kPa) automatically. The ultrasound elastography image in Figure 1 displays a colour-coded representation, and the region of interest (ROI) was identified on the lens tissue. The sizes of the ROIs were fixed to 2 mm in all cases and placed on four different parts of the eye: the temporal and nasal sides.

Measurement variability and repeatability

As per the readings obtained from ultrasound elastography at a center of the lens, multiple scans (at least three per subject) were conducted for each subject. The output remains consistent, showing uniform values. As depicted in the figure, four instances display identical readings, confirming the uniformity of the elastographic data at the specified location. This consistency across multiple cases ensures the accuracy and reliability of the ultrasound elastography measurements. The table (Table 1) presents data from four subjects, each undergoing three measurements in the same eye, randomly selected from different cases.

Data analysis

The data analysis was conducted using IBM SPSS, which yielded a descriptive summary (minimum, maximum, mean, and standard deviation) of the degree of elasticity, presbyopia, and accommodation. The data were summarized as mean and standard deviation as they were normally distributed. Correlations (strength of association) between the parameters, including the degree of elasticity and age, presbyopia was assessed using Pearson Correlation coefficient (the recommended standard test for this purpose) as a mean of hypothesis generation. All these variables were analyzed as continuous variables on their actual scale. Correlation coefficient ranging from 0.1 to 0.3 was considered low, 0.4 to 0.6 as moderate, and 0.7–1.0 as high, respectively. A p-value of less or equal 0.05 was considered for a significant correlation and relationship between the variables. Multivariate regression analysis was not used because assessing the nature of association or prediction (the main purpose of regression) was not the focus of our study.

Results

Patients' baseline characteristics

A total of 84 participants were recruited for this study, with 40 identified as non-presbyopic and 44 identified as presbyopic, The majority of study participants were between the ages of 40 and 50, comprising 41% of the total subjects. This was followed by participants aged 31 to 39, who made up 32% of the study group, These age characteristics of the study participants are detailed in (Table 2).

Visual acuity and refractive error data

The investigation into visual acuity revealed notable findings among the participants, based on measurements targeting levels of 6/6, 6/9, and 6/12 (Table 3). Among the eyes examined:

- 78 eyes exhibited a visual acuity of 6/6:
- 34 cases had normal vision without refractive errors.
- 44 cases required corrective lenses to achieve 6/6 vision.
- 5 cases had a visual acuity of 6/9, all corrected with lenses.
- 1 case had a visual acuity of 6/12, corrected with lenses.

Table 1. Measurement variability.

Subject	Measurement 1	Measurement 2	Measurement 3
1	7.2	7.2	7.2
2	12.1	12.1	12.1
3	4.3	4.3	4.3
4	5.2	5.2	5.2

Table 2. Participants' baseline characteristics.

Age group	Frequency	Percentage	Mean (SD)
19–30	13	15.0	39.61 (9.60)
31–39	27	32.0	
40–50	34	41.0	
51–60	10	12.0	
61–65	0	0.0	

Table 3. Distribution of participants based on visual acuity and refractive error assessment.

Variables	Frequency	Percentage
Visual acuity		
6/6	78	92.9
6/9	5	6.0
6/12	1	1.2
Abnormal values (ametropia)	50	59.5
Type of refractive error		
Myopic	42	84.0
Hypermetropic	6	12.0
Mixed	2	4.0

There was no significant difference in visual acuity between non-presbyopic and presbyopic subjects ($p = 0.588$)

The analysis of refractive errors identified 42 cases of myopia, ranging from simple to moderate, including those with myopic astigmatism. Additionally, there were six cases of simple hypermetropia with astigmatism and two cases of mixed astigmatism. Overall, 12% of the observed cases had hypermetropia, and 4% had astigmatism.

Amplitude of accommodation and degree of presbyopia data

The study quantitatively assesses accommodation data by dividing participants into two age groups: 19-39 years old (non-presbyopia cohort). In this group, accommodation measurements range from 4.0 to 14.0 diopters. A clear trend shows that accommodation decreases with age, which significantly impacts the ability to focus on near objects. Within the second group of 44 individuals aged 40 to 65 years diagnosed with presbyopia, the ability to see objects up close significantly decreases with age. Accommodation measurements in this group range from 1.00 to 4.00 diopters, with an average of 2.75 diopters, highlighting the decline in near vision acuity with age in the presbyopic cohort.

The overall findings indicate that the mean amplitude of accommodation (AA) is 5.25 ± 3.16 D, which falls within the normal range. However, there is a significant difference between non-presbyopia and presbyopia subjects. The

AA for presbyopia subjects (2.73 ± 0.88 D) is significantly lower than that for non-presbyopia subjects (5.25 ± 3.16 D) ($t = 13.54$, $p = 0.001$). The AA for presbyopia subjects is also below the normal range (4D–8D). Among the subjects, 47.6% ($n = 40$) have insufficient AA, 35.7% ($n = 30$) have normal AA, and 16.7% ($n = 14$) have excess AA. All subjects with insufficient AA are presbyopic, while those with excess AA are non-presbyopic. The proportion of subjects with normal AA is higher among non-presbyopia (86.7%, $n = 26$) compared to presbyopia subjects (13.3%, $n = 4$).

Starting in the fourth decade of life, there is a noticeable decline in the eye's ability to accommodate, leading to reduce near vision acuity. This reduction necessitates the use of a convex lens, whose power matches the level of accommodation lost due to presbyopia. The strength of this lens, known as the "add," reflects the extent of accommodation insufficiency. This corrective method compensates for the eye's diminished ability to focus on close objects, with lens power directly proportional to the degree of presbyopia. The average degree of presbyopia was 0.83 ± 0.87 SD. Among the participants, 25% were classified as having mild presbyopia, 62% had moderate presbyopia, and 13% had advanced presbyopia.

Figure 2 shows the scatter plots for the correlation patterns between age and (a) accommodation, (b) degree of presbyopia. Figure 3 presents scatter plots illustrating between presbyopia measurement and the age in presbyopia group.

All descriptive results for Amplitude of accommodation and degree of presbyopia are presented in Table 4.

Lens elasticity data

The elasticity degree, measured in kilopascals (kPa), exhibited distinct patterns among the groups studied. The overall mean elasticity was determined to be 10.24 ± 3.67 kPa. For individuals without presbyopia, the elasticity mean was recorded at 6.98 ± 1.73 kPa, indicating a lower degree compared to the overall mean. Conversely, those with presbyopia displayed a markedly higher degree mean of 13.21 ± 2.09 kPa, surpassing both the overall mean and the elasticity observed in the non-presbyopic group. With less degree is higher elasticity degree and higher degree indicated less elasticity and vice versa. There is a significant difference in lens elasticity between two groups. Table 5 details the findings regarding the degree of lens elasticity. When analyzing both the presbyopia and non-presbyopia groups, we found that in the non-presbyopic group, the elasticity varied randomly among individuals of different ages. This suggests that lens elasticity, when within the normal range, behaves like a vital physiological parameter that does not necessarily depend on age. In contrast, in the presbyopic group, elasticity showed a systematic change with age specifically, the elasticity value increased with older age, indicating a decrease in actual lens elasticity.

Correlation lens elasticity with age groups, Amplitude of accommodation and presbyopia degree

The analysis, using a two-tailed Pearson bivariate correlation. Statistical significance was defined as a p-value less than 0.05, a strong and significant association between lens elasticity and age across the entire sample ($r = 0.838$,

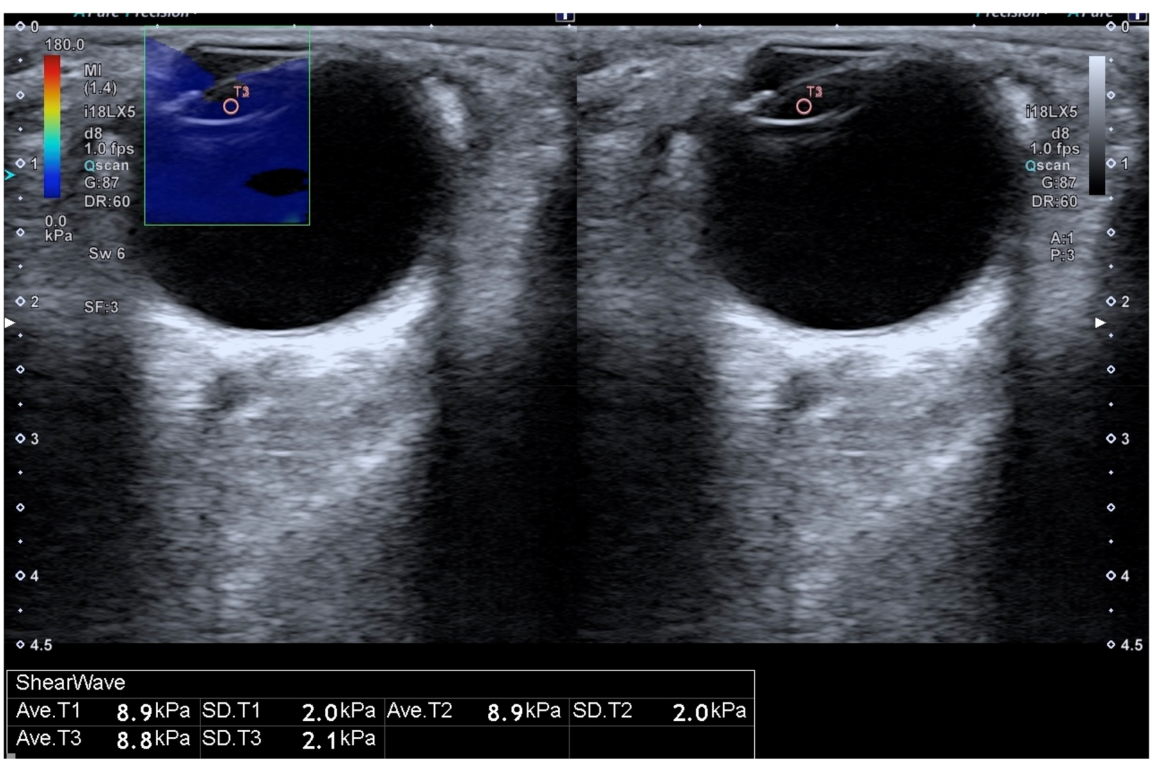

Figure 2. Ultrasound elastography image displays a colour-coded representation, and the region of interest (ROI) identified on the lens tissue.

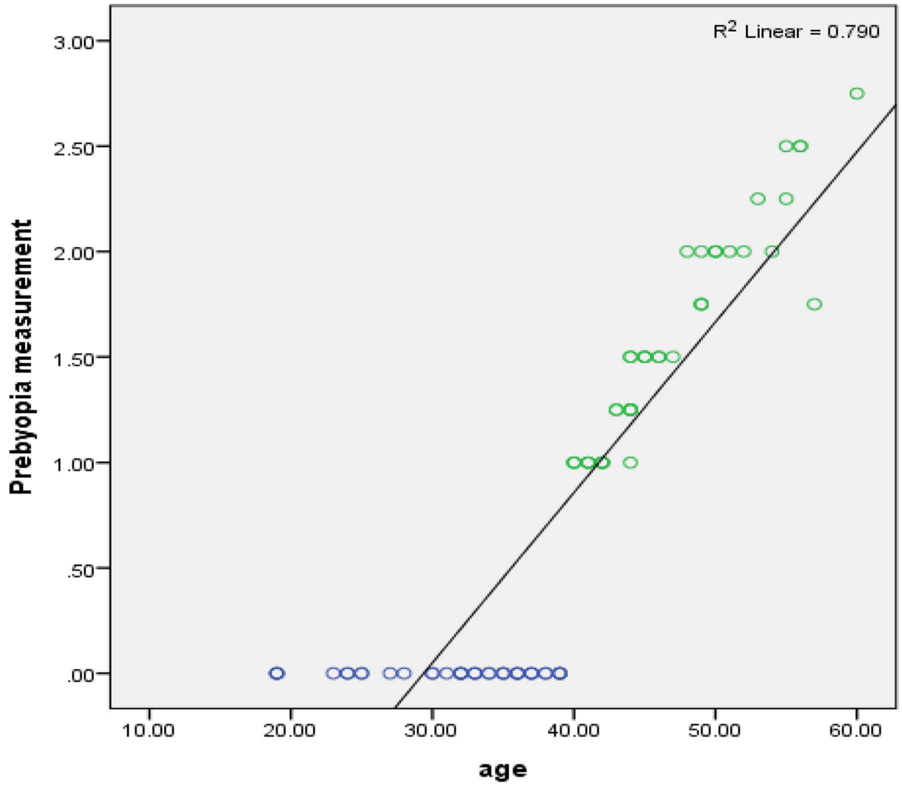

Figure 3. Scatter plots show the correlation patterns between age and degree of presbyopia.

Table 4. Descriptive results for Amplitude of accommodation and presbyopia degree.

	Age (years old)			
Variables	19–30	31–39	40–50	51–60
Amplitude of Accommodation				
Mean ± SD	9.69 ± 2.45	6.88 ± 2.00	2.82 ± 0.77	2.13 ± 0.92
Insufficiency		0	1 (2.5)	30 (75.0)
Normal	5 (16.7)	23 (76.7)	1 (3.3)	1 (3.3)
Excess	8 (57.1)	6 (42.9)	0	0
Degree of Presbyopia				
Mean ± SD			1.42 ± 0.35	2.25 ± 0.31
Mild (< +1.25D)		0	0	11 (25)
Moderate (+1.25D – +2.0D)	0	0	27 (62)	0
Advance (> +2.0D)	0	0	0 (0)	6 (13)

$p = 0.001$). However, within the non-presbyopic group, the correlation was weak ($r = 0.289$, $p = 0.70$). In contrast, a significant correlation was observed between lens elasticity and age in the presbyopic group ($r = 0.674$, $p = 0.002$). Additionally, the degree of presbyopia demonstrated a strong correlation with lens elasticity ($r = 0.612$, $p = 0.001$), indicating a significant relationship at the 0.01 level (two-tailed). Figure 4 presents scatter plots illustrating the patterns of correlation between lens elasticity and age in whole cases.

Lens accommodation exhibited a strong, significant inverse correlation with the degree of lens elasticity. Specifically, in the non-presbyopic group, the correlation coefficient was -0.358, while in the presbyopic group, it was -0.493. The degree of presbyopia showed a direct, strong, and significant correlation with the degree of lens elasticity ($r = 0.612$, $p = 0.001$). Figure 5 presents scatter plots illustrating the patterns of correlation between lens elasticity and presbyopia measurement.

Discussion

This study assessed the suitability of SWE in measuring important ocular parameters, including presbyopia and accommodation determining the relationship between the among various age groups. We found that approximately one-third of the participants' eyes were emmetropic (normal eye vision) and a visual acuity of 6/6. Meanwhile, 59.5% of the participants had ametropia – characterized by various forms of refractive errors. A high prevalence of myopia was observed at 84% relative to hypermetropia and mixed astigmatism at 12% and 4%, respectively. These findings are consistent with the prevalence of myopia reported among sampled individuals in South East Asian countries, including Japan, China and Singapore.[32–34] In contrast, the prevalence of myopia among persons aged 40 years and above in China and Myanmar ranged from 8% to 51%.[34,35]

In this study, further investigation was conducted within the myopic group. The analysis examined the relationship between lens elasticity and refractive error, revealing no significant correlation ($p = 0.456$). Additionally, when the myopic group was analyzed separately in relation to lens elasticity, no significant correlation was found ($p = 0.659$). Further analysis indicated that axial length measurements (mean = 24.40 mm, SD = 1.311 mm) suggested that the primary cause of myopia is an increased axial length beyond the normal range.

The study demonstrates a strong correlation between lens elasticity and age in the presbyopia group, whereas in the non-presbyopia group, the correlation was weak. This finding strengthens the study's hypothesis, as the lens elasticity in the non-presbyopia group remained within the normal

Table 5. Descriptive results for the lens elasticity degree.

	Frequency (percentage)					
Ultrasound elastography measurement	All	Non-Presbyopia	Presbyopia	MD (SE)	t-test	*p*-value
Elasticity degree (kPa)	10.24 ± 3.67	6.98 ± 1.73	13.21 ± 2.09	−6.23 (0.42)	−14.79	<0.001*

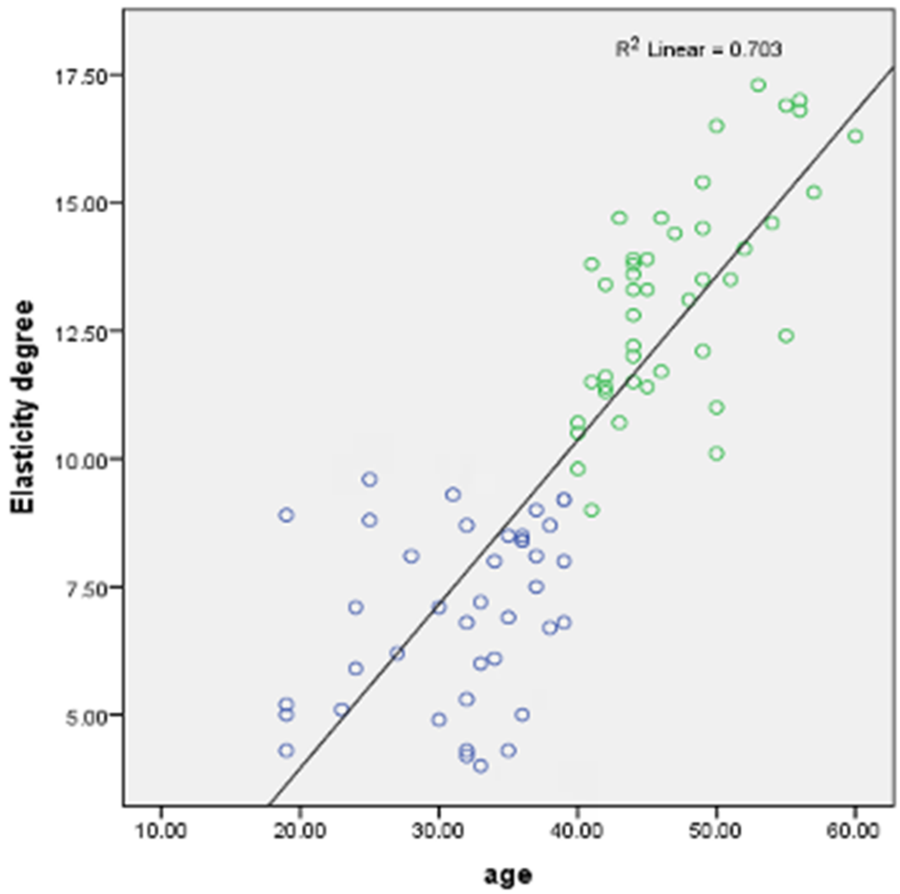

Figure 4. Scatter plots show the correlation patterns between elasticity degree and age.

range. This variability is similar to that observed in vital signs, where individual differences exist but generally fall within a normal range. In contrast, the presbyopia group exhibited a significant decline in lens elasticity with advancing age.

The low prevalence of hypermetropia aligns with the participants' average age, which is below 55 years old, as well as the eligibility criteria such as absence of eye defects and medication that may increase the intraocular pressure or fluid retention. Previous studies have shown that ophthalmic intervention are commonly performed in individuals aged 60 years and above,[33] but such age groups were not recruited in the present study. As found in this study, a wider prevalence of hypermetropia was reported compared to myopia among individuals aged 40 years above in China at 1% but greater than 50% in Iran, USA, and Nigeria.[33,36] These discrepancies may stem from factors such as genetic, lifestyle, race, and ocular conditions.

We also observed a high number of individuals with presbyopia cases, especially among those aged 40–60 years. This finding corroborates the reports in a previous study in which the participants' age was positively associated with the prevalence of presbyopia and increasing at a rate of 0.87.[37] Furthermore, the positive correlation between age and lens elasticity and presbyopia as gleaned from the SWE assessments has important implications. The result suggests that age affects the biomechanical qualities of the lens, including problems in the lens tissue that may influence the degree of stretching.[38] Similar findings were reported in earlier studies in which other quantification techniques were applied to measure ocular and biometric parameters.[39] The elasticity properties of the lens, particularly by altering the lens shape during accommodation, are vital when attempting to focus on near objects. A number of studies have shown that the degree of accommodation of the human lens declines with age, which is associated with increased stiffness and lower elasticity.[36,40,41] The biological properties of the lens change significantly with age; there is a strong link between accommodation and the ability to change the shape of the lens, which in effect, is dependent on the elasticity of the lens tissue.[41]

Another important finding obtained from using SWE in this research was the significant positive correlation presbyopia. The association between myopia aligns with the results from previous studies. For instance, O' Donell et al. (2011) recorded a significant difference in lens thickness across

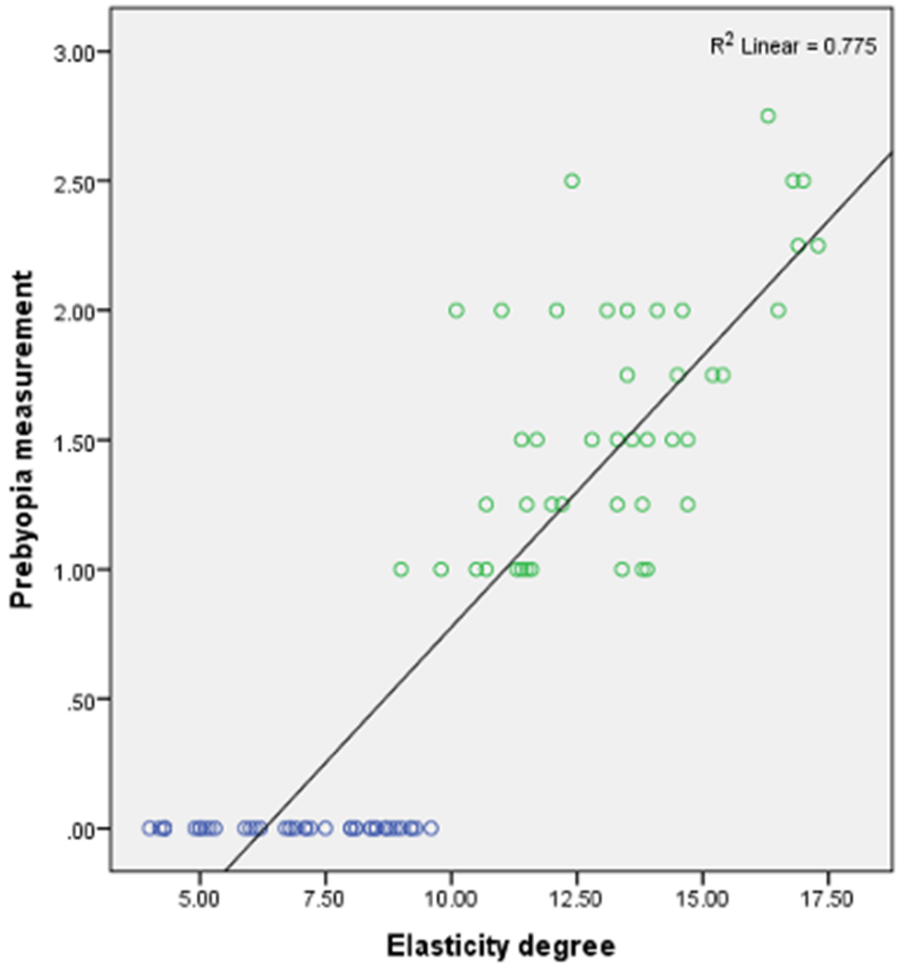

Figure 5. Scatter plots show the correlation patterns between elasticity degree and presbyopia degree.

two refractive categories.[41] A study among children of various age groups revealed significant differences in the lens thickness.[42] Although the latter studies used different assessment techniques compared to the SWE employed in the present study, our findings support the theory of a positive association between age and the thickening of crystalline.[24,43] However, a study by Xie et al. (2009) depicted no significant relationship between different refractive age groups and lens thickness. This discrepancy may stem from the alteration in the refractive index of the crystalline lens, thereby causing a difference in the lens thickness between age groups.[44]

The findings from this study reflect the successful achievement of the research objectives. Previous research has shown that the elasticity of the lens changes as a person ages, which can affect the accuracy of ultrasound SWE. The results suggest that ultrasound SWE method used in this study is reliable and robust, even in the presence of changes in lens elasticity associated with age. Since the SWE was successfully used in measuring the biometric parameters and assessing the relationships between the hypothesized variables, this technique may be considered by future researchers since it also offers other important attributes such as convenience and simplicity. In addition, it offers a non-invasive approach to assessing the biomechanical properties of various eye parts, including normal and abnormal eyes. Therefore, this metric may have potential applications in both clinical and research settings, providing valuable insights into the mechanisms of various ocular diseases and conditions.

The limitations of this study are well-acknowledged. This was a cross-sectional study and only the association between biomedical properties of the lens was investigated among a sample of 84 individuals. As a result, no casual inference could be deduced from the findings. In addition, the results may not be generalizable since the data were collected from persons visiting one hospital in Serdang, Selangor. The small sample size also made it difficult to control for age and gender in the analysis. Future studies may attempt to address these limitations to facilitate more robust and generalizable findings. An additional limitation of the study pertains to the use of ARFI imaging, which necessitates a higher mechanical index (MI) than conventional ophthalmic ultrasound. Although the MI employed (0.6) was within the acceptable range defined by the FDA's Track 3 designation for elastography and did not result in any observed adverse effects, it nonetheless exceeds the ophthalmic-specific threshold of 0.23. While extensive precautions were taken—including adherence to ALARA principles, brief excitation pulse durations, and institutional ethical approval—future studies should include direct evaluation of thermal and mechanical safety outcomes in ocular tissues to further validate the long-term safety of ARFI in ophthalmic applications.

Conclusion

The findings from this study reflect the successful achievement of the research objectives. The results suggest that the ultrasound SWE method used in this study is reliable and robust, even in the presence of age-related changes in lens elasticity. Since SWE successfully measured biometric parameters (age, presbyopia, and accommodation capacity) and assessed the relationships between the hypothesized variables, this technique may be considered by future researchers due to its convenience and simplicity. Additionally, SWE offers a noninvasive approach to evaluating the biomechanical properties of various eye structures, including both normal and abnormal eyes. This technique may have potential applications in clinical and research settings, providing valuable insights into the mechanisms of various ocular diseases and conditions.

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Author contributions

We confirm that all authors made substantial contributions to the conception and design of this study and to the interpretation of relevant literature. Each author was involved in writing and/or revising the manuscript for intellectual content. Specific contributions include data collection and management by A. Qader, A. Kudri, and N. Bahari; data analysis and interpretation by A. Qader, R. Saleh, M. Zain, E. Rahim, and R. Saleh; and manuscript writing, drafting, reviewing, and approval by all authors.

Disclosure statement

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Data availability statement

The data that support the findings of this study are part of a PhD programme and as such are not publicly available due to privacy and security concerns.

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