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M-mode and tissue doppler estimation of age and gender-specific normative values of aortic stiffness in healthy adults

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ABSTRACT

Background: The elastic properties of the aorta are modified in numerous cardiovascular (CV) and non-cardiovascular (non-CV) diseases. Multiple studies have evaluated aortic stiffness in myriads of disease state, albeit only a few Indian studies have estimated the normal values of aortic stiffness in the healthy population. To the best of our knowledge, till date, no research has been undertaken to determine the age and gender-specific value ranges of aortic stiffness parameters in healthy subjects. Hence, in the present study, we endeavored to estimate these values in our distinctive study groups of healthy adults.

Methods: This was a prospective observational study in which 58 healthy adults were enrolled during the turbulent Corona pandemic. The study group consisted of individuals of either sex within the age range of 18 to 60 years and was divided into six groups arbitrarily. Exhaustive M-mode and Tissue Doppler Imaging (TDI) was performed by a 4-dimensional XStrain echocardiography (4D XStrain E) system for extensive evaluation of multiple M-mode and TDI-derived parameters of aortic stiffness and superior wall velocities of ascending aorta.

Result: Aortic Systolic diameter (AOS), Aortic Diastolic diameter (AOD), aortic strain, and elasticity modulus were greater in males. On the contrary aortic superior wall velocities (SAO: Aortic superior wall velocity, EAO: Early diastolic velocity, and AAO: Late diastole velocity) were higher in females. Increasing age leads to a decline in the majority of stiffness parameters derived by M-mode echocardiography. Correspondingly, EAO showed a deterioration with advancing age.

Conclusion: The authors report a normal range of M-mode and TDI-derived values of aortic stiffness of ascending aorta in healthy Indian adults. The difference in magnitude of aortic elasticity indices has been demonstrated in men and women, as well as in different subsets of the study group.

KEYWORDS

Aortic stiffness; Aortic elasticity; 4D XStrain Echocardiography; TDI of Aorta; Healthy adults; Covid-19 pandemic

ARTICLE HISTORY

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Introduction

Functional properties of the aorta are the major determinants of normal cardiovascular (CV) function [1]. Increments in aortic stiffness and reduction in aortic distensibility (indicators of elastic properties of the aorta) are associated with coronary artery disease [2,3]. Aortic elasticity is an established methodology for risk stratification of atherosclerotic heart disease, myocardial infarction, stroke, and heart failure [3]. Numerous methods have been employed for the evaluation of aortic elasticity, namely Magnetic Resonance Imaging (MRI), aortic angiography applanation tonometry, velocity vector imaging, and gated radionuclide angiography [4-7]. Moreover, M-mode and Tissue Doppler Imaging (TDI) of the ascending aorta is also used to estimate its
elastic properties [8-13].

The elastic properties of the aorta are modified in numerous CV and non-cardiovascular (non-CV) diseases. Hypertension, mitral valve prolapse, aortic aneurysms, coronary artery disease, and heart failure being the major CV disease, cystic fibrosis, pregnancy, chronic kidney disease, hypothyroidism, sarcoidosis, α1-antitrypsin deficiency, and diabetes, being the non-CV diseases, altering the aortic stiffness properties (Figures 1 and 2) [14-23]. Earlier, aortic stiffness has been evaluated in myriads of disease states, even though only a few Indian studies have assessed the normal values of aortic stiffness parameters in healthy population [24,25]. Till date, no research has been undertaken to determine the age and gender-specific value ranges of aortic stiffness parameters in healthy subjects. Hence, in the present study, we endeavored to determine the above-mentioned normative values in our distinctive study groups of healthy population.

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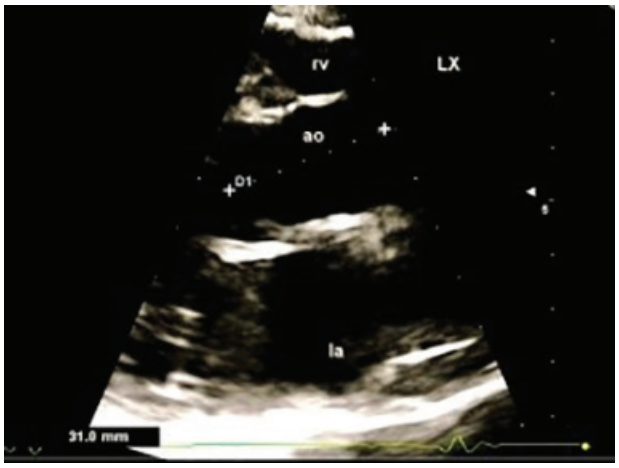

Figure 1. Measurement of aortic diameter obtained at 3 cm above the aortic cusps.

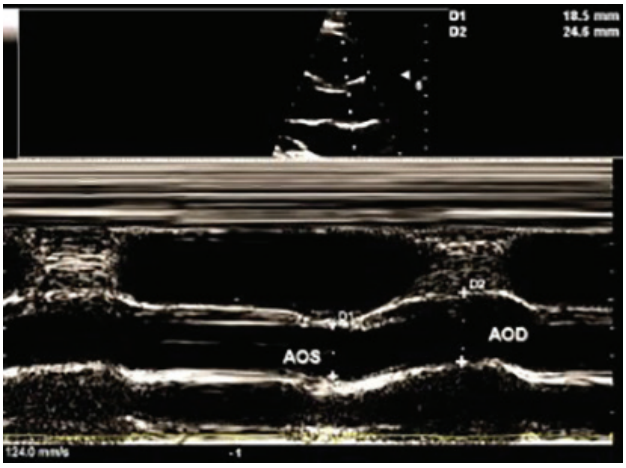

Figure 2. Aorta visualized on M-mode. The movement of aortic wall appears as two wavy lines. The space between the two lines is the aortic lumen. Systolic and diastolic diameters are measured on M-mode.

Materials and Methods

This study was carried out at Prakash Heart Station and Diagnostic Centre, Lucknow, India. This was a prospective, observational study in which 258 healthy Indian adults were recruited, and later on, 200 cases were omitted due to inferior image quality. Finally, 58 participants were enrolled during a period of 9 months from September 2021 to May 2022. The study group consisted of individuals of either sex within the age range of 18 to 60 years and was divided into six groups arbitrarily:

Group A: Overall study population subjects from 18-30 years of age.
Group B: Overall study population subjects from 31-60 years of age.
Group C: Male subjects from 18-30 years of age.
Group D: Female subjects from 18-30 years of age.
Group E: Male subjects from 31-60 years of age.
Group F: Female subjects from 31-60 years of age.

Those participants were included if they were asymptomatic with a normal physical examination, BMI 23 or less, waist size 85 cm2 or less in men and 80 cm2 or less in women, free from overt CV disease, not receiving any drugs, nonsmoker, nontobacco chewer, nondiabetic, nonhypertensive according to JNC-8 guidelines, having normal thyroid and lipid profiles, normal resting electrocardiogram (ECG) in sinus rhythm with a normal two-dimensional echocardiography and Treadmill Stress ECG. Besides the above inclusion criteria, 4-dimensional EF % >50%, derived by volumetric analysis using 4D XStrain E, was another important requirement.

Those individuals were excluded if there was presence of diabetes mellitus, neurological or psychiatric illness, malignancy, CAD, aortic root abnormalities and aortic dilatation thyroid disease, valvular heart disease, history of cardiac rhythm abnormalities, heart failure, systemic hypertension, and significant pulmonary hypertension.

The study procedure was approved by the Institutional Ethics Board of Prakash Heart Station and Diagnostics, Lucknow, India. All subjects or their guardians gave their written informed consent prior to data collection and furthermore, confidentiality of patient information was maintained.

Data collection and study procedure

All patients underwent full history taking, clinical examination, and a standard resting 12-lead ECG. A negative Covid-19 reverse transcription polymerase chain reaction report conducted within 72 hours prior to the data of enrollment and echocardiography was the essential requirement because the study was conducted during the raging Covid-19 pandemic.

Biochemical and hormonal assessment

After 12 hours of overnight fasting, blood samples were withdrawn for HBAIC, T3T4TSH, serum creatinine, total cholesterol, triglycerides, low-density cholesterol, and high-density cholesterol. These estimations were done to rule out the presence of diabetes mellitus, hypothyroid or hyperthyroid state, renal failure, and dyslipidemia.

Blood pressure measurement

Blood pressure (BP) levels were measured from the right brachial artery at the level of the heart with a mercury sphygmomanometer after resting for at least 5 minutes in the supine position. Three measurements were performed at least 2 minutes apart, and the average of the closest two readings was recorded. A pressure drop rate of approximately 2mm hg/sec was applied, and Korotkoff's phases I and V were used for systolic and diastolic BP (Systolic blood pressure (SBP) and diastolic blood pressure (DBP), respectively) levels. All BP measurements were made by a cardiologist. Pulse pressure (PP) was calculated as systolic minus diastolic BP.

Echocardiography

All echocardiographic evaluations were performed by the author, using MyLab X7 4D XStrain echocardiography machine, Esaote, Italy. The images were acquired using a harmonic variable frequency (1MHz-5MHz) electronic single-crystal array transducer with the subject lying in the left lateral decubitus position.

Conventional echocardiography

M-mode, 2-dimensional, and pulsed wave doppler (PWD) echocardiography was performed from parasternal long-axis, short-axis, and apical 3 chamber, 4 chamber, and 2 chamber views and the following data were derived: Interventricular

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septum thickness in diastolic and systolic (IVSd and IVSs respectively), left ventricular posterior wall thickness in diastole and systole (LVPWd and LVPWs, respectively), left ventricular end-diastole and end-systole volumes (LVEDV and LVESV, respectively). Moreover, 2-dimensional ejection fraction (2D-EF%) by biplane Simpson's method, LV mass in diastole (LV Mass d), and cardiac output (CO) were also determined. The Cardiac Index was calculated by dividing the CO by body surface area (BSA). By using PWD, early diastolic velocity (E), late diastolic velocity (A), and E/A ratio was measured.

Aortic stiffness assessment by M-mode echocardiography of ascending aorta

Systolic and diastolic inner diameter of the ascending aorta were recorded by M-Mode echocardiography 3cm above the aorta valve in a parasternal long-axis image. Aortic systolic diameter (AOS) was measured at the maximum anterior motion of the aorta, and aortic diastolic diameter (AOD) was measured at the peak of the QRS complex on the recorded ECG (Figures 1 and 2). All the parameters were computed, and the average of 5 consecutive cycles was calculated. Aortic distensibility (D), aortic stiffness index (SI), and other elasticity parameters were determined by using the following formulas [26, 27].

Aortic distensibility = 2x AOS–AOD/[(SBP–DBP)X AOD (106. cm2 dyn-1)]

Aortic stiffness index = ln (SBP/DBP)/ [AOS – AOD]/AOD](pure number), ln = natural logarithm

Aortic pulsatile change (APC) = AOS – AOD (cm)

Aortic systolic index (ASysI)

Aortic diastolic index (ADI)

Aortic pulsatile index (API)

ASysI, ADI, and API were calculated by dividing AOS, AOD, and APC by BSA, respectively.

Aortic compliance (AS) = (AOS-AOD/SBP-DBP) (cm/mmHg)

Elasticity modulus (EM) = (SBP-DBP)/([AOS-AOD]/AOD) (Pa)

Aortic strain (AS) = (SAO - AOD) X100/AOD (%)

TDI of ascending aorta

Aortic upper-wall velocities were measured by TDI at the same point as in the M-mode measurements (Figure 3), and gain and filter settings were adjusted to optimize the image. High temporal resolution (>100 frames/s) and a sweep speed set to 100 mm/s were used. The TDI of expansion peak velocity during systole (SAO) and early (EAO) and late (AAO) contraction peak velocities during diastole were obtained with a 1-mm sample volume size.

The resulting velocities were recorded for 5 consecutive cardiac cycles and stored for later playback and analysis. The following data were estimated by TDI of the superior wall of ascending aorta (Figure 4).

Tissue doppler echocardiography of left ventricle

TDI of LV was conducted by placing the PWD sample volume at the lateral mitral annulus in apical four-chamber view, and early diastolic velocity (E') and E/E' ratio was determined in the TDI mode.

4-dimensional XStrain speckle-tracking echocardiography

From the apical position, two-dimensional cine loops were acquired from two-chamber, three-chamber, and four-chamber views. A high-quality ECG signal was must for proper gating, and a minimum of three cardiac cycles were acquired for each cine loop. The study was performed with a frame rate between 40 and 75 fps and then stored digitally on a hard disk for offline analysis by software package XStrainTM advanced technology TOMTEC GMGH 3D/4D rendering BeutelTM computation capabilities (Figure 5) [28].

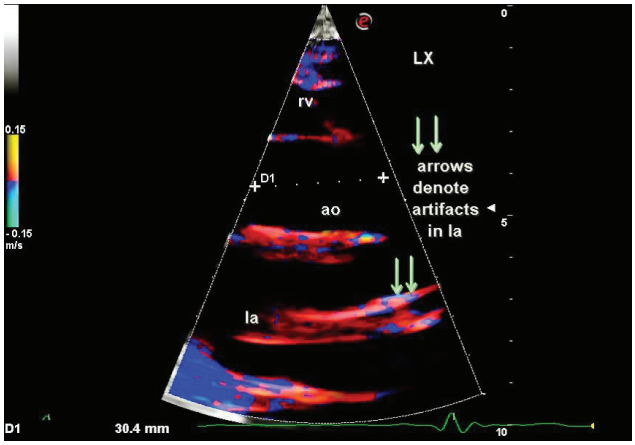

Figure 3. Tissue Doppler Imaging of the ascending aorta. The measurements were made at a level of 3 cm above the aortic cusps, at the same point as that for M-mode echocardiography.

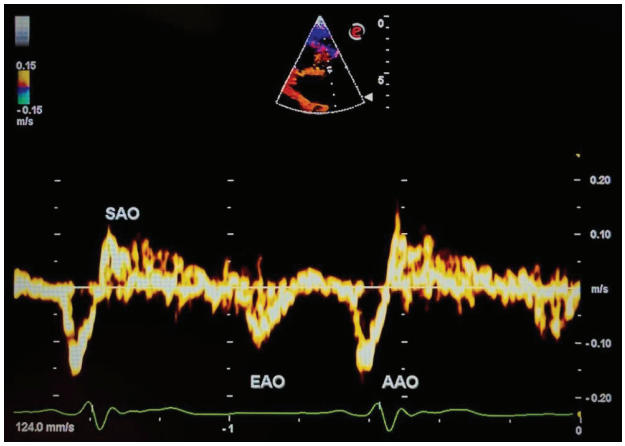

Figure 4. Aortic superior wall velocity measurements with tissue doppler imaging. SAO: systolic superior wall velocity, EAO: early diastolic superior wall velocity, AAO: late diastolic superior wall velocity. SAO: aortic superior wall velocity in systole was calculated at the same point used in M-mode measurement.

The LV endocardial and epicardial borders were identified, tracked, and highlighted by a semiautomatic tool AHS Aided Heart Segmentation Esaote, for border segmentation. Thirteen equidistant tracking points were automatically incorporated along the LV endocardial border, and where necessary manual adjustment of endocardial tracing was done. The software automatically divided the LV wall into 6 segments, and then the acquired cine loop of each apical view was tracked frame by frame throughout the cardiac cycle. The cine loops with inadequate tracing quality and with any signs of arrhythmia were excluded.

The LV bull's eye depiction according to 17-segment model was generated by XStrain 4D software by integrating the results of each set of cine loops [29,30]. XStrain-4D software created a 3D reconstruction for calculating LV volumes and EF

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[31], and XStrain 4D-EF by the "Beutel Mode" method (TOMTEC, Germany) (Figure 6) [32].

Statistical analysis

Statistical analysis was performed with Microsoft excel® (Excel 2019. Microsoft Corp. Seattle Washington. USA). The continuous variables are expressed as mean ± SD. The 95% confidence interval of mean was also calculated. Enrolled participants were stratified according to Group A-F, age: <30 years and >31 years and gender: male and female. Comparison of various datasets between men and women and between different age groups was performed by Students t-test for independent groups. The level of significance used was <0.05. A higher t value having a probability <0.05 was marked significant. A p-value <0.01 was marked as highly significant.

Result

We performed an aortic stiffness assessment of ascending aorta in 58 healthy Indian adults of age 18-60 years, with a mean 32.16 ± 11.82 years, free from overt CV disease (Table 1). The study population was arbitrarily divided into six groups: Group A from 18-30 years of age, Group B from 31-60 years of age, Group C, male subjects of 18-30 years, Group D, female

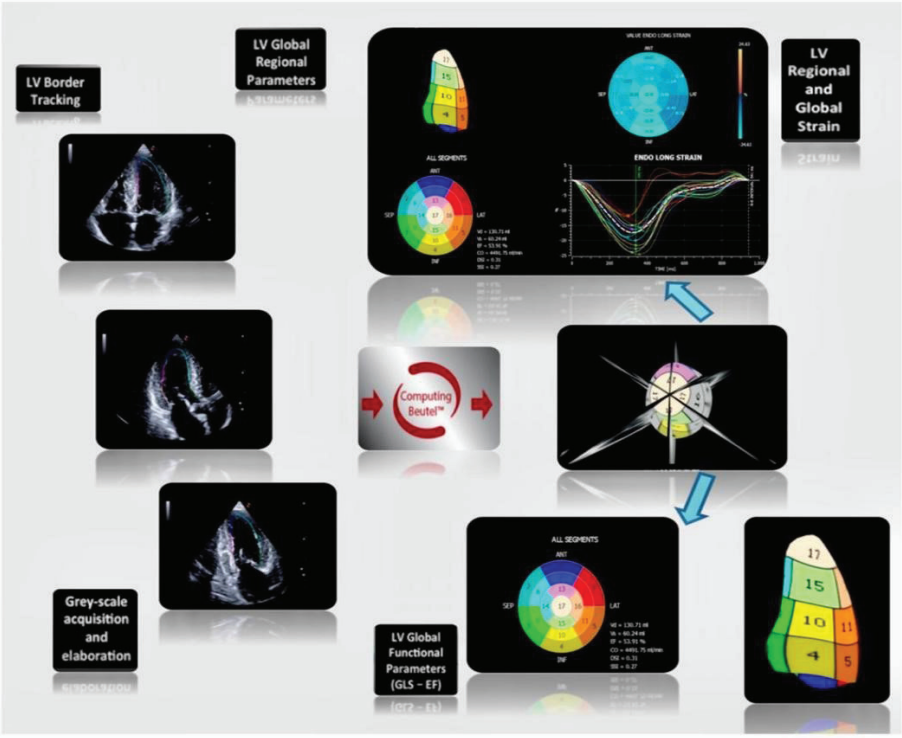

Figure 5. XStrain 4D global LV analysis. At the end of each scanning section, the three apical views are acquired. Then, after left ventricular (LV) endocardial border tracking, the software analyzes LV regional deformation parameters. Finally, the Beutel 3D reconstruction allows quantification of global LV function (global longitudinal strain (GLS) ejection fraction) XStrainTM 4D.

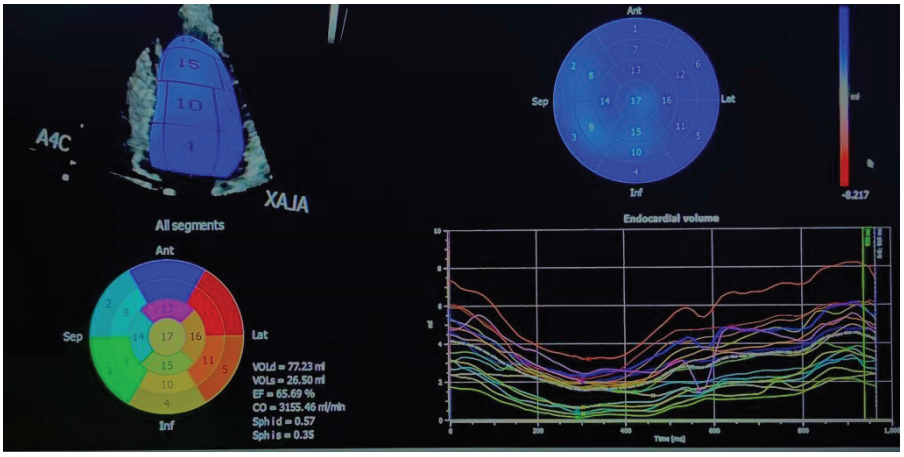

Figure 6. XStrain 4D software created a 3D reconstruction for calculating LV volumes and XStain 4D-EF by the "Beutel Mode" method (TOMTEC, Germany). The following 4D XStrain E derived volumetric parameters were statistically analyzed. Volumetric data: sphericity index in diastole and systole, LVEDV, LVESV, 4D-EF%, and CO.

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subjects of 18-30 years, Group E, male subjects of 31-60 years and Group F, female participants of 31-60 years.

Demographic data

The mean BSA of the participants was 1.67 ± 0.18 sq. meters. There were 38 males and 20 females with a mean age of 30.53 ± 12.22 years and 35.25 ± 10.61 years respectively, and a mean BSA of 1.72 ± 0.16 sq. meter and 1.57 ± 0.18 sq. meter respectively (Table 1). The mean age in Group A-E was 23.13 ± 4.33 years, 42.52 ± 8.71 years, 21.68 ± 3.95 years, 26.66 ± 3.08 years, 42.68 ± 8.61 years and 42.27 ± 9.25 years respectively and mean BSA was 1.64 ± 0.17m2, 1.40 ± 0.2m2, 1.67 ± 0.14m2, 1.56 ± 0.18m2, 1.78 ± 0.16m2, 1.56 ± 0.17m2, respectively (Table 2).

Conventional echocardiography data

LA size, E/A ratio, lateral TDI E' and lateral TDI E/E' ratio are surrogate measurements for assessment of diastolic function of LV and LVIDd, LVEDV, EPSS, and EF% are representative of systolic function. In our study, LA size, E/A ratio, lateral TDI E', LVIDd, and LVEDV were significantly higher in males (p<0.01) even though CO & 2D-EF% were higher in females (p<0.01) (Table 3). Additionally, E/A ratio and 2D-EF% were lower in Group B when compared with Group A (p<0.01), suggesting a reduction in diastolic & systolic function of LV with increasing age.

Table 1. Demographic data (n=58).

Variables	Study population (n:58)	Male (N-38) Mean ± SD	Female (N-20) Mean ± SD
Age (yrs)	32.16 ± 11.82	30.53 ± 12.22	35.25 ± 10.61
Weight (kg)	61.45 ± 11.08	64.18 ± 10.44	56.25 ± 10.62
HT (cm)	164.45 ± 8.62	167.42 ± 6.84	158.80 ± 8.99
BSA (m2)	1.67 ± 0.18	1.72 ± 0.16	1.57 ± 0.18
BMI	22.56 ± 2.66	22.77 ± 2.52	22.17 ± 2.93
SBP (mmhg)	118.28 ± 10.97	118.26 ± 10.58	118.30 ± 11.95
DBP (mmhg)	76.66 ± 6.58	76.74 ± 6.60	76.50 ± 6.71
Heart Rate (bpm)	80.45 ± 14.52	77.89 ± 13.06	85.30 ± 16.21

NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)

4-dimensional volumetric data

The sphericity index in diastole and systole, LVEDV and LVESV were higher in males (p<0.01). Nevertheless, 4D-EF% was more in females (p<0.01) (Table 4). We noticed a decline in sphericity indices in Group B as compared to Group A (p<0.05), suggesting a significant change in LV geometry with increasing age.

Table 2. Demographic data (n=58).

Variables	Groups A (n=31)Mean ± SD	B (n=27) Mean ± SD	C (n=22) Mean ± SD	D (n=9) Mean ± SD	E (n=16) Mean ± SD	F (n=11) Mean ± SD
Age (yrs)	23.13 ± 4.33	42.52 ± 8.71	21.68 ± 3.95	26.66 ± 3.08	42.68 ± 8.61	42.27 ± 9.25
Weight (kg)	59.58 ± 10.71	63.59 ± 11.31	61.22 ± 10.00	55.55 ± 11.88	68.25 ± 9.90	56.81 ± 10.02
HT (cm)	163.87 ± 6.51	165.11 ± 10.65	165.54 ± 5.40	159.77 ± 7.44	170 ± 7.88	158 ± 10.37
BSA (m2)	1.64 ± 0.17	1.40 ± 0.20	1.67 ± 0.14	1.56 ± 0.18	1.78 ± 0.16	1.56 ± 0.17
BMI	22.03 ± 2.71	23.17 ± 2.50	22.22 ± 2.58	21.56 ± 3.11	23.52 ± 2.28	22.65 ± 2.81
SBP (mmhg)	115.35 ± 11.33	121.63 ± 9.69	115.90 ± 11.78	114 ± 10.67	121.5 ± 7.91	121.81 ± 12.24
DBP (mmhg)	74.71 ± 6.19	78.89 ± 6.41	74.36 ± 5.84	75.55 ± 7.26	80 ± 6.32	77.27 ± 6.46
Heart rate (bpm)	78.84 ± 13.29	82.30 ± 15.87	77.09 ± 13.22	83.11 ± 13.22	79 ± 13.19	87.09 ± 18.74

NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years), Group C: Male Subjects (age 18-30yrs), Group D: Female Subjects-(age 18-30yrs), Group E: Male Subjects-(age 31-60yrs), Group F: Female Subjects-(age 31-60yrs)

M-mode data of aortic stiffness

AOS, AOD, pulsatile change, pulsatile index, aortic strain and elasticity modulus were greater in males (p<0.01), and aortic distensibility was insignificant elevated (p=NS). On the contrary, aortic systolic index and aortic diastolic index were higher in females (p<0.01) (Table 5). Furthermore, pulsatile change, pulsatile index, and aortic strain were lower in Group B as compared to Group A (P<0.01), demonstrating a decline of these stiffness parameters with increasing age.

TDI data of aortic stiffness

SAO, EAO, and AAO were higher in females (p<0.01) (Table 6). It was also observed that EAO was lower in Group B,

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Table 3. Conventional echocardiography data (n=58).

Variables	Study population (n:58)	Male (N-38) Mean ± SD	Female (N-20) Mean ± SD	P P-Val.	Sig	Age wise group (Years)Group A (Overall) (n=31)	Group B (Overall) (n=27)	P-Val.	Sig
EPSS (mm)	0.60 ± 0.32	0.57 ± 0.26	0.66 ± 0.41	<0.01	**	0.58 ± 0.37	0.63 ± 0.26	0.71	NS
Left Atrium (cm)	2.80 ± 0.53	2.83 ± 0.55	2.75 ± 0.49	<0.01	**	2.68 ± 0.40	2.94 ± 0.63	0.59	NS
IVS d (cm)	0.73 ± 0.16	0.73 ± 0.17	0.73 ± 0.13	<0.01	**	0.70 ± 0.16	0.76 ± 0.14	0.5	NS
LVID d (cm)	4.70 ± 0.47	4.84 ± 0.40	4.42 ± 0.48	<0.01	**	4.68 ± 0.46	4.72 ± 0.48	0.07	NS
LVPW d (cm)	0.77 ± 0.13	0.79 ± 0.13	0.73 ± 0.12	<0.01	**	0.73 ± 0.13	0.82 ± 0.12	0.69	NS
LVEDV (ml)	63.38 ± 42.32	74.90 ± 43.46	41.49 ± 30.40	<0.01	**	79.61 ± 43.10	44.75 ± 33.28	0.22	NS
LV Mass d (gm)	114.40 ± 31.20	122.00 ± 29.74	99.95 ± 29.37	<0.01	**	108.10 ± 26.82	121.63 ± 34.68	0.84	NS
CO. (L/min)	5.43 ± 1.67	5.43 ± 1.46	5.43 ± 2.07	<0.01	**	5.14 ± 1.37	5.75 ± 1.94	0.81	NS
E/A Ratio	1.41 ± 0.54	1.44 ± 0.53	1.33 ± 0.56	<0.01	**	1.73 ± 0.48	1.03 ± 0.32	<0.01	**
Lateral TDI E'	6.92 ± 7.34	8.38 ± 7.56	4.15 ± 6.17	<0.01	**	10.71 ± 7.57	2.56 ± 3.90	<0.01	**
Lateral TDI E/E' Ratio	0.40 ± 0.40	0.32 ± 0.33	0.55 ± 0.48	0.7	NS	0.25 ± 0.38	0.57 ± 0.35	<0.01	**
2D-EF (%)	0.65 ± 0.07	0.62 ± 0.07	0.69 ± 0.06	<0.01	**	0.65 ± 0.07	0.64 ± 0.07	<0.05	*

EPSS: Epoint septal separation, IVSd: Interventricular septum in diastole, LVPwD: Left ventricular posterior wall in diastole, LVID: Left ventricular, internal dimension LVEDV: Left ventricular end-diastole volume, CO: Cardiac output, TDI: Tissue doppler imaging, EF: Ejection fraction.
NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years)

Table 4. 4-dimensional volumetric data (n=58).

Variables	Study population (n:58)	Male (N-38) Mean ± SD	Female (N-20) Mean ± SD	P P-Val.	Sig	Age wise group (Years)Group A (Overall) (n=31)	Group B (Overall) (n=27)	P-Val.	Sig
Sphericity index d	0.44 ± 0.12	0.45 ± 0.13	0.42 ± 0.10	<0.01	**	0.46 ± 0.14	0.42 ± 0.09	<0.05	*
Sphericity index s	0.37 ± 0.12	0.38 ± 0.13	0.35 ± 0.12	<0.01	**	0.39 ± 0.14	0.34 ± 0.11	<0.05	*
LVEDV (ml)	78.47 ± 17.12	81.07± 17.14	73.52 ± 16.39	<0.01	**	78.18 ± 17.99	78.80 ± 16.40	0.14	NS
LVESV (ml)	35.06 ± 9.30	36.27 ± 8.71	32.74 ± 10.16	<0.01	**	35.50 ± 9.21	34.55 ± 9.56	0.09	NS
EF (%)	55.81 ± 5.24	55.50 ± 4.52	56.40 ± 6.48	<0.01	**	55.10 ± 4.59	56.63 ± 5.88	0.13	NS
CO (L/min)	3.37 ± 0.83	3.43 ± 0.78	3.26 ± 0.94	<0.01	**	3.29 ± 0.76	3.45 ± 0.92	0.34	NS
Cardiac Index (L/mm/m2)	2.02 ± 0.47	1.99 ± 0.45	2.07 ± 0.52	<0.01	**	2.01 ± 0.45	2.03 ± 0.51	0.17	NS

LVEDV: Left ventricular end-diastolic volume, LVESV: Left ventricular end-systolic volume, EF: Ejection fraction, CO: Cardiac output
NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years)

indicating a deterioration of early diastolic upper wall velocity with aging. Contrarily SAO and AAO showed insignificant (p=NS) increments with increasing age.

Comparison of aortic stiffness data in various subjects

On comparing Group C and D (male and female subjects of age 18-30 years), it was shown that AOS, AOD, and aortic stiffness index and elasticity modulus were greater in males of 18-30 years of age (p<0.01), even though the aortic strain was higher in females (p<0.01) (Table 7). Similarly, SAO, AAO, and EAO reflected lower values in Group D than Group C, indicating diminished aortic superior wall velocities in female subjects of age 18-30 years of age.

In addition, when we analyzed the data of Group E and F (male and female subjects of age 31-60 years), it was noted that AOS, AOD, and aortic strain values were higher in Group E than Group F. Conversely, the SAO, AAO, and EAO values were more in Group F, even though insignificantly (p=NS).

Interestingly, only aortic strain was lower in Group E when compared to Group C (P<0.01), implying that aortic strain was deteriorating with increasing age in male subjects (Table 8). On the contrary AOS, AOD, aortic stiffness index, and elasticity modulus were insignificantly higher in Group E (p=NS). We also observed that SAO values were higher and EAO values were lower in Group E (p<0.01) when compared with Group C.

Subsequently, on collating the aortic stiffness data in female subjects (Group D and F), we found higher values of AOS, AOD, aortic stiffness index, and elasticity modulus in Group F

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than D (p<0.05, p<0.05, p<0.01, p<0.05), suggesting that in female adults that there is a decline in these stiffness parameters with advancing age. Simultaneously, SAO and EAO were also higher in Group F (p<0.05).

We have extensively estimated the age and gender-specific values of aortic stiffness in various subsets of our study population. Here, we are furnishing summarized values (Table 9) of the above-mentioned parameters discerned from the current study. This table is particularly meant for contemporary and prospective medical researchers to conceptualize further on these interesting original findings.

Table 5. Comparison of M-Mode data of ascending aorta data (n=58).

Variables	Study population (n:58)	Male (N-38)	Female (N-20)	P		Age wise group (Years)		P	
		Mean ± SD	Mean ± SD	P val.	Sig	Group A (Overall) (n=31)	Group B (Overall) (n=27)	P val.	Sig
AOS	2.68 ± 0.40	2.73 ± 0.38	2.59 ± 0.42	<0.01	**	2.53 ± 0.36	2.86 ± 0.37	0.85	NS
AOD	2.22 ± 0.40	2.23 ± 0.38	2.18 ± 0.45	<0.01	**	2.02 ± 0.33	2.44 ± 0.35	0.52	NS
Pulsatile change	0.47 ± 0.14	0.49 ± 0.14	0.42 ± 0.14	<0.01	**	0.51 ± 0.12	0.42 ± 0.15	<0.01	**
Ao syst. index	1.62 ± 0.26	1.59 ± 0.22	1.67 ± 0.32	<0.01	**	1.55 ± 0.22	1.70 ± 0.27	0.59	NS
Ao diast. index	1.34 ± 0.24	1.30 ± 0.20	1.40 ± 0.31	<0.01	**	1.23 ± 0.19	1.45 ± 0.24	0.76	NS
Pulsatile index	0.28 ± 0.09	0.29 ± 0.09	0.27 ± 0.10	<0.01	**	0.31 ± 0.08	0.25 ± 0.10	<0.01	**
Ao distensbility (10^{-6} cm^2 dyn^{-1})	0.01 ± 0.02	0.02 ± 0.03	0.01 ± 0.01	0.09	NS	0.02 ± 0.03	0.01 ± 0.01	0.07	NS
Ao stiffness index	1.99 ± 0.47	1.95 ± 0.38	2.08 ± 0.61	<0.01	**	1.76 ± 0.30	2.26 ± 0.49	0.22	NS
Ao strain (%)	22.78 ± 8.86	23.58 ± 8.55	21.25 ± 9.45	<0.01	**	27.06 ± 7.70	17.85 ± 7.51	<0.01	**
Elasticity modulus (Pa)	204.16 ± 102.32	200.42 ± 80.95	211.26 ± 136.27	<0.01	**	159.29 ± 61.37	255.67 ± 115.98	<0.05	*

AOS: Aortic dimension in systole, AOD: Aortic dimension in diastole, Ao: Aorta
NS=Not Significant (p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years)

Table 6. Comparison of TDI data of ascending aorta data (n=58).

Variables	Study population (n:58)	Male (N-38)	Female (N-20)	P		Age wise group (Years)		P	
		Mean ± SD	Mean ± SD	P val.	Sig	Group A (Overall) (n=31)	Group B (Overall) (n=27)	P val.	Sig
SAO (cm/sec)	1.10 ± 0.35	1.08 ± 0.35	1.14 ± 0.36	<0.01	**	1.06 ± 0.29	1.14 ± 0.41	0.57	NS
EAO (cm/sec)	0.94 ± 0.30	0.93 ± 0.32	0.96 ± 0.27	<0.01	**	0.98 ± 0.28	0.89 ± 0.33	<0.05	*
AAO (cm/sec)	1.14 ± 0.47	1.13 ± 0.44	1.15 ± 0.53	<0.01	**	1.07 ± 0.42	1.21 ± 0.51	0.89	NS

TDI: Tissue doppler imaging, SAO: Systolic upper velocity, EAO: Early diastolic aortic upper wall velocity, AAO: late diastolic upper wall velocity.
NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years)

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Table 7. Comparison of aortic stiffness and tissue doppler imaging data(n=58) contd.

Variables	Groups		P		Groups		P	
	C (n=22)	D (n=9)	P value	Sig	E (n=16)	F (n=11)	P value	Sig
Aortic Stiffness Parameters								
AOS	2.59 ± 0.38	2.38 ± 0.26	0.000003	**	2.92 ± 0.29	2.77 ± 0.46	0.01	*
AOD	2.06 ± 0.37	1.90 ± 0.20	0.000003	**	2.47 ± 0.25	2.41 ± 0.48	0.02	*
Ao distensbility (10^{-6} cm^2 dyn^{-1})	0.02 ± 0.04	0.02 ± 0.01	0.11	NS	0.01 ± 0.004	0.01 ± 0.01	0.62	NS
Ao stiffness index	1.79 ± 0.31	1.67 ± 0.27	0.000005	**	2.16 ± 0.38	2.41 ± 0.61	0.14	NS
Ao strain (%)	26.77 ± 8.23	27.78 ± 6.63	0.0001	**	19.19 ± 7.08	15.91 ± 8.04	0.01	*
Elasticity modulus (Pa)	167.84 ± 64.25	138.40 ± 50.97	0.00001	**	245.22 ± 81.77	270.88 ± 156.58	0.25	NS
Tissue Doppler Imaging Parameters								
SAO (cm/sec)	1.10 ± 0.25	0.95 ± 0.35	0.000003	**	1.04 ± 0.46	1.29 ± 0.30	0.44	NS
EAO (cm/sec)	1.03 ± 0.28	0.88 ± 0.26	0.000002	**	0.79 ± 0.33	1.03 ± 0.27	0.61	NS
AAO (cm/sec)	1.10 ± 0.38	0.99 ± 0.54	0.00005	**	1.16 ± 0.53	1.29 ± 0.50	0.24	NS

AOS: Aortic dimension in systole, AOD: Aortic dimension in diastole, Ao: Aorta, TDI: Tissue doppler imaging, SAO: Systolic upper velocity, EAO: Early diastolic, aortic upper wall velocity, AAO: late diastolic upper wall velocity, Ao: Aortic
NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group C: Male Subjects (age 18-30yrs), Group D: Female Subjects-(age 18-30yrs), Group E: Male Subjects-(age 31-60yrs), Group F: Female Subjects-(age 31-60yrs)

Table 8. Comparison of aortic stiffness and tissue doppler imaging data (n=58) contd.

Variables	Groups		P		Groups		P	
	C (n=22)	E (n=16)	P value	Sig	D (n=9)	F (n=11)	P value	Sig
Aortic Stiffnes Parameters								
AOS	2.59 ± 0.38	2.92 ± 0.29	0.14	NS	2.38 ± 0.26	2.77 ± 0.46	0.03	*
AOD	2.06 ± 0.37	2.47 ± 0.25	0.3	NS	1.90 ± 0.20	2.41 ± 0.48	0.01	*
Ao distensbility (10^{-6} cm^2 dyn^{-1})	0.02 ± 0.04	0.01 ± 0.004	0.1	NS	0.02 ± 0.01	0.01 ± 0.01	0.58	NS
Ao stiffness Index	1.79 ± 0.31	2.16 ± 0.38	0.34	NS	1.67 ± 0.27	2.41 ± 0.61	0.002	**
Ao strain (%)	26.77 ± 8.23	19.19 ± 7.08	0.0001	**	27.78 ± 6.63	15.91 ± 8.04	0.15	NS
Elasticity modulus (Pa)	167.84 ± 64.25	245.22 ± 81.77	0.74	NS	138.40 ± 50.97	270.88 ± 156.58	0.01	*
Tissue Doppler Imaging Parameters								
SAO (cm/sec)	1.10 ± 0.25	1.04 ± 0.46	0.02	*	0.95 ± 0.35	1.29 ± 0.30	0.01	*
EAO (cm/sec)	1.03 ± 0.28	0.79 ± 0.33	0.0004	**	0.88 ± 0.26	1.03 ± 0.27	0.05	*
AAO (cm/sec)	1.10 ± 0.38	1.16 ± 0.53	0.13	NS	0.99 ± 0.54	1.29 ± 0.50	0.07	NS

AOS: Aortic dimension in systole, AOD: Aortic dimension in diastole, Ao: Aorta TDI: Tissue doppler imaging, SAO: Systolic upper velocity, EAO: Early diastolic aortic, upper wall velocity, AAO: ate diastolic upper wall velocity, Ao: Aortic
NS=Not Significant(p>0.05), ** Highly Significant=(p<0.01), * Significant=(p<0.05)
Group C: Male Subjects (age 18-30yrs), Group D: Female Subjects-(age 18-30yrs), Group E: Male Subjects-(age 31-60yrs), Group F: Female Subjects-(age 31-60yrs)

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Table 9. Summary of aortic stiffness parameter.

Variables	Study population (n:58)	Male (n-38)	Female (n-20)	Groups				
		Mean ± SD	Mean ± SD	A (n=31) Mean ± SD	B (n=27) Mean ± SD	C (n=22) Mean ± SD	D (n=9) Mean ± SD	E (n=16) Mean ± SD
M-mode parameter								
Ao distensbility (10^{-6} cm^2 dyn^{-1})	0.01 ± 0.02	0.02 ± 0.03	0.01 ± 0.01	0.02 ± 0.03	0.01 ± 0.01	0.02 ± 0.04	0.02 ± 0.01	0.01 ± 0.004
Ao stiffness Index	1.99 ± 0.47	1.95 ± 0.38	2.08 ± 0.61	1.76 ± 0.30	2.26 ± 0.49	1.79 ± 0.31	1.67 ± 0.27	2.16 ± 0.38
Ao strain (%)	22.78 ± 8.86	23.58 ± 8.55	21.25 ± 9.45	27.06 ± 7.70	17.85 ± 7.51	26.77 ± 8.23	27.78 ± 6.63	19.19 ± 7.08
Elasticity modulus (Pa)	204.16 ± 102.32	200.42 ± 80.95	211.26 ± 136.27	159.29 ± 61.37	255.67 ± 115.98	167.84 ± 64.25	138.40 ± 50.97	245.22 ± 81.77
Tissue Doppler Imaging Parameters								
SAO (cm/sec)	1.10 ± 0.35	1.08 ± 0.35	1.14 ± 0.36	1.06 ± 0.29	1.14 ± 0.41	1.10 ± 0.25	0.95 ± 0.35	1.04 ± 0.46
EAO (cm/sec)	0.94 ± 0.30	0.93 ± 0.32	0.96 ± 0.27	0.98 ± 0.28	0.89 ± 0.33	1.03 ± 0.28	0.88 ± 0.26	0.79 ± 0.33
AAO (cm/sec)	1.14 ± 0.47	1.13 ± 0.44	1.15 ± 0.53	1.07 ± 0.42	1.21 ± 0.51	1.10 ± 0.38	0.99 ± 0.54	1.16 ± 0.53

NB: All values in the above table are MEAN ± SD
SAO: Systolic upper velocity, EAO: Early diatolic aortic upper wall velocity, AAO: late diastolic upper wall velocity, Ao: Aortic
Group A: overall subjects (age18-30 years), Group B: overall subjects (age 30-60 years), Group C: Male Subjects (age 18-30yrs), Group D: Female Subjects (age 18-30yrs), Group E: Male Subjects (age 31-60yrs), Group F: Female Subjects (age 31-60yrs)

Discussion

It is well known that increased aortic stiffness has been associated with impaired LV systolic and diastolic functions. The association between increased stiffness and LV systolic dysfunction has been demonstrated in a previous study [33], particularly along the long axis. The relation is often attributed to increased hemodynamic load caused by stiffer arteries [34, 35]. An alternative explanation for the observed relation between aortic stiffness and LV systolic function is the direct mechanical ventricular-vascular coupling. Systolic contraction shortens the LV long axis by pulling the aortic annulus and sino-tubular junction of the aorta towards the LV apex, which moves minimally during systole [36-39]. The combination of aortic annulus displacement along with sparse movement of the aortic arch implies that there is a substantial longitudinal stretch of the ascending aorta during systole [39-41].

Abhayaratna et al. (2006) assessed the relationship of arterial stiffness with LV diastolic dysfunction in 188 elderly individuals and found a significant correlation between central pulse pressure and severity of diastolic dysfunction and concluded that increased arterial stiffness was associated with more severe left ventricular diastolic dysfunction [42]. The arterial stiffness index establishes the elastic properties of the arterial wall in a manner relatively independent of blood pressure, and aortic distensibility evaluates the ability of the arteries to dilate during the cardiac cycle [13,43-49].
Aortic stiffness and aortic distensibility have been examined with VVI and pulse wave velocity (PWV) [45, 50]. However, VVI is a new and invasive method requiring transesophageal echocardiography, which limits its routine use in clinical practice. Also, PWV is not the ideal procedure to evaluate aortic elasticity properties since it is affected by many factors including hematological and physiological characteristics, as well as heart rate and BP variations [51-53].

Direct measurements of aortic elasticity by TDI, which is a practical method for measuring diameter changes related to wall movements, may provide further help than other methods described above because it is not affected by hematological and CV physiology [54-56]. Multiple articles have shown a link between loss of elasticity in major arteries and CV adverse events [55, 56]. In the Framingham Cardiology study, after over 20 years of monitoring, increased pulse pressure, which is an indication of large vessel wall stiffness, has been shown to increase coronary artery disease risk in the middle and older age group who had no clinical coronary artery disease [57].
Hence, the determination of normal value ranges of aortic stiffness parameters is imperative because only the normal values can be compared to the values obtained in different disease states.

A considerable amount of literature is available on the adverse impact caused by various disease states on the aortic stiffness parameters; nevertheless, it is exceptionally rare to find a study depicting these values in a healthy population. After a deep search of the literature, we could only come across a solitary study [24] that has recently endeavored to put forward the normal values ranges of aortic stiffness properties in healthy populations by 2-dimensional and 4-dimensional XStrain echocardiography. There were 72 healthy participants in the 2-dimensional group and 30 individuals in the 4-d XStrain group. The results are analogous to the current study,

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even though there were a small number of subjects in 4-d XStrain group.

In the study of elasticity properties of ascending aorta in healthy children and adolescents [58], 165 subjects were enrolled with a mean age of 11.92 ± 4.0 years. The mean age in our study group was 32.16 ± 11.82 years and to compare their data with the present study would not be feasible. Another research study investigated the effects of subclinical hypothyroidism on elastic properties of the ascending [16]. This study had strict inclusion criteria, and they recruited 48 healthy controls with a mean age of 42 ± 11 years. The values of their control group are incongruous with our study, and the reason seems to be the disparity of mean age of the controls of their study and the healthy subjects of the present study. Correspondingly Vitarelli et al. (2010) reported in their 80 healthy controls, two-dimensional M-mode and TDI-guided ascending aorta wall stiffness parameters [13]. The mean age was 49 ± 17 years, and the values of stiffness index (SI), aortic distensibility (D), elastic modulus (EM), SAO, AAO, and EAO reflected gross incongruity with our study group. The divergence of results may be because of dissimilarities in the mean age of our study group and their control group (mean age 49 ± 17 years).

Güngör et al. (2014) showed that aortic stiffness is increased in patients with premature coronary artery disease (CAD) [14]. In their study, there were 50 patients with acute coronary syndrome (ACS) and 70 age-sex-matched controls. However, in their control groups there were 26 smokers, and several were having hypertension, diabetes, and hyperlipidemia controlled by medication. Nevertheless, the mean age in their study group was 34 ± 3.9 years, which is similar to our study. Since this study included, in their control group, volunteers who were current smokers, controlled hypertensives, diabetics, and hyperlipidemics therefore to collate the results of aortic stiffness in their control group with our study would not be meaningful.

Earlier studies mentioned above are in some way or the other inharmonious with the present research work. We have extensively compared our data in healthy populations by constructing various subsets of groups and then collating the values amongst them in a judicious manner. The main results of our study can be outlined as follows: (i) we provided exhaustive data on several parameters of Aortic stiffness determined by M-mode and TDI echocardiography, (ii) our study group was arbitrarily divided into six groups A-E, (iii) 4-dimensional volumetric data: sphericity index, LVEDV, and LVESV were higher in males, and importantly, 4d-EF was more in females, (iv) AOS, AOD, Aortic strain, and elasticity modulus were greater in males, (v) on the contrary aortic superior wall velocities (SAO, EAO, AAO) were higher in females, (vi) increasing age leads to a decline in parameters of sphericity index, and majority of stiffness parameters derived by M-mode echocardiography, (vii) correspondingly EAO determined by TDI of superior wall of aorta, showed a deterioration with advancing age.

Study Limitations

The echocardiographic method of determining the aortic stiffness using mathematical equations may have some limitations [54,55]. Firstly, BP and pulse pressure measured at the level of brachial artery may not exactly reflect aortic pulse pressure, and secondly, BP measurement and aortic echocardiographic assessment cannot be carried out simultaneously. All the participants are of Indian ethnicity, and the normal value ranges of the present study cannot be anticipated to be identical with other ethnic groups, particularly Caucasians. (3) Our study had the modest number of subjects because it was undertaken during the raging coronavirus pandemic, and to encounter a normal, healthy subject during this period was an arduous task. Moreover, this is a single-center experience.

Recommendations and Future Research Directions

The authors recommend, in the future, large-scale multiple centers randomized controlled trials enrolling hundreds of healthy subjects to further investigate these important properties of aortic stiffness and to firmly establish the normal value ranges of aortic stiffness in a healthy population.

Conclusions

The authors have reported a normal range of M-mode and TDI-derived values of aortic stiffness of ascending aorta in healthy Indian adults. The difference in magnitude of aortic elasticity indices has been demonstrated in men and women, as well as in different subsets of the study group.

Disclosure statement

No potential conflict of interest was reported by the authors.

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