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Published in:
Journal of Physiology

DOI:
[10.1113/JP271621](https://doi.org/10.1113/JP271621)

2015

[Link to publication](#)

Citation for published version (APA):

Steding Ehrenborg, K., Boushel, R. C., Calbet, J. A., Åkeson, P., & Mortensen, S. P. (2015). Left ventricular AV-plane displacement is preserved with lifelong endurance training and is the main determinant of maximal cardiac output. *Journal of Physiology*, 593(23), 5157-5166. <https://doi.org/10.1113/JP271621>

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5

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Left ventricular AV-plane displacement is preserved with lifelong endurance training and is the main determinant of maximal cardiac output

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Running title: Preserved AVPD with lifelong endurance training

Key words: cardiac pumping; ageing; athletes; cardiac magnetic resonance imaging

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Key Points summary

- Ageing has negative effects on cardiac function
- Endurance training in young subjects is known to improve cardiac function and the ability to deliver blood to exercising tissue.
- This study shows that lifelong endurance training maintains cardiac pumping function at a level similar to sedentary young subjects and by the same mechanisms.
- Healthy untrained elderly subjects have maintained cardiac pumping function but uses compensatory mechanisms similar to what is seen in patients with heart failure.
- Healthy ageing includes regular physical activity in order to maintain cardiac function.

Abstract

Background: Age-related decline in cardiac function can be prevented or postponed by lifelong endurance training. However, effects of normal ageing as well as of lifelong endurance exercise on longitudinal and radial contribution to stroke volume are unknown. The aim of this study was to determine resting longitudinal and radial pumping in elderly athletes, sedentary elderly and young sedentary subjects. Furthermore, we aimed to investigate determinants of maximal cardiac output in elderly.

Methods: 8 elderly athletes (63±4 years), 7 elderly sedentary (66±4 years) and 10 young sedentary subjects (29±4 years) underwent cardiac MR. All subjects underwent maximal exercise testing and for elderly subjects maximal cardiac output during cycling was determined using dye dilution technique.

Results: Longitudinal and radial contribution to stroke volume did not differ between groups (longitudinal left ventricle (LV) 52-65%, $p=0.12$, right ventricle (RV) 77-87%, $p=0.16$, radial 7.9-8.6%, $p=1.0$). Left ventricular atrioventricular plane displacement (AVPD) was higher in elderly athletes and young sedentary compared to elderly sedentary (14±3 mm, 15±2 mm, and 11±1 mm, respectively $p<0.05$). There was no difference between groups for RVAVPD ($p=0.2$). LVAVPD was an independent predictor of maximal cardiac output ($R^2=0.61$, $p<0.01$, $\beta=0.78$).

Conclusion: Longitudinal and radial contribution to stroke volume did not differ between groups. However, how longitudinal pumping was achieved differed, where elderly athletes and young sedentary showed similar AVPD whilst it was significantly lower in elderly sedentary. Instead elderly sedentary achieved longitudinal pumping through increased short-axis area of the ventricle. Large AVPD was a determinant of maximal cardiac output and exercise capacity.

Abbreviations

AVPD. atrioventricular plane displacement: BSA. body surface area. CO. cardiac output: ECG. electrocardiography. EDV. end-diastolic volumes: ESV. end-systolic volumes: ICG-indocyanine green: LA. left atrium. LV. left ventricle: LVM. left ventricular mass: MR. magnetic resonance: RA. right atrium: RV. right ventricle. SV. stroke volume: SVlong. longitudinal contribution to stroke volume: THV. total heart volume.

Background

Normal healthy ageing decreases ventricular volumes and also systolic and diastolic functions are decreased (Kitzman *et al.*, 1991; Pearson *et al.*, 1991; Hudsmith *et al.*, 2005; Maceira *et al.*, 2006b, a). Several studies over the past century have shown that in young and elderly athletes, long term endurance training increase cardiac volumes and improves function (Henschen, 1899; Nicolai & Zuntz, 1914; Seals *et al.*, 1994; Bouvier *et al.*, 2001; Scharhag *et al.*, 2002; Arbab-Zadeh *et al.*, 2004; Steding *et al.*, 2010). However, it is unknown how lifelong endurance training affects cardiac function measured as longitudinal and radial contribution to stroke volume (SV).

Longitudinal pumping has been shown to be of importance for ventricular function allowing the atria and ventricle to fill reciprocally (Hamilton & Rompf, 1932). If there was only radial pumping, ejection fraction of the left ventricle would be <30% (Henein & Gibson, 1999). Furthermore, radial pumping is of importance for ventricular filling where the rapid relaxation after radial contraction causes a drop in ventricular pressure and suction of blood into the ventricle from the atrium (Katz, 1930; Brecher, 1956; Yellin *et al.*, 1990). Thus, maintained cardiac pumping mechanics are necessary for optimal cardiac output delivery. Using cardiac MR, these new aspects of the elderly heart can be investigated.

The purpose of this study was therefore to explore the hypothesis that longitudinal and radial contribution to SV is affected by age and that lifelong endurance training can prevent or reduce these effects. We aimed to determine cardiac volumes and longitudinal and radial contribution to SV at rest in three groups; elderly healthy sedentary subjects, elderly athletes with lifelong experience of endurance training and young healthy sedentary subjects. Furthermore, we aimed to investigate the relationship between the functional capacity of the heart to deliver cardiac output during maximal exercise related to cardiac volumes and function.

Methods

The study was approved by the ethics committee of Copenhagen, Denmark (elderly subjects) and the regional ethics committee in Lund, Sweden (young subjects) and was conducted in accordance with the Declaration of Helsinki. All study subjects provided oral and written informed consent. Cardiac MR examinations of elderly subjects were performed at Danish Centre for Magnetic Resonance, Hvidovre Hospital, Denmark and invasive exercise measurements were performed at the Copenhagen Muscle Research Centre, Rigshospitalet, Denmark on separate days. Cardiac MR examinations of young subjects were performed at Skåne University Hospital in Lund, Sweden.

Study population

Eight male elderly athletes aged 63 ± 4 years, seven matched sedentary control subjects aged 66 ± 4 years and ten young sedentary subjects aged 29 ± 4 were included. Elderly athletes were active in road cycling and had a history of training more than five hours of high-intensity exercise per week for the last 30 years. Elderly sedentary and young sedentary did not

participate in any regular physical training. None of the subjects had been diagnosed with cardiovascular disease, renal dysfunction, insulin resistance, diabetes, or hypercholesterolemia. Resting blood pressure was measured using an automatic cuff (Omron M6 comfort, Kyoto; Japan) or a manual sphygmomanometer.

Cardiac magnetic resonance imaging

Cardiac MR was performed in the supine position using a 1.5T Siemens Avanto scanner (Siemens, Erlangen, Germany) with a body matrix coil or in a 1.5T Philips Achieva (Philips, Best, The Netherlands) with a 32 channel coil. Images of the heart were acquired using steady-state free precession sequences with retrospective ECG triggering. After defining the long-axis orientation of the heart, short-axis images covering the entire heart from the base of the atria to the apex of the ventricles were obtained. Resting heart rate was obtained from ECG during image acquisition.

Measurements of cardiac volumes

All measurements were performed using the software Segment (Segment 1.9; <http://segment.heiberg.se>) (Heiberg *et al.*, 2010).

Left and right atrial maximal volumes were defined as the largest volume just before the start of the diastolic filling of the ventricles. Volumes were measured in short-axis images using planimetry and the endocardial borders of the atria were manually defined as previously described (Mosen & Steding-Ehrenborg, 2014). Left and right ventricular end-diastolic and end-systolic volumes (EDV, ESV) and left ventricular mass (LVM) were measured in short-axis images, manually defining endocardial and epicardial borders of the ventricular myocardium. Papillary muscles were not included in LVM. Total heart volume (THV) was measured in short-axis images as previously described (Carlsson *et al.*, 2004) and

was defined as the volume of all structures within the pericardium, including myocardium, blood pool, atria, pericardial fluid and the proximal parts of the great vessels (Figure 1).

Longitudinal and radial pumping

Atrioventricular plane displacement (AVPD) was determined from long-axis images (Carlsson *et al.*, 2007b; Steding-Ehrenborg *et al.*, 2013). In short, the atrioventricular plane was tracked over the cardiac cycle and AVPD was defined as the distance between the location of the atrioventricular plane in end-diastole and its location in end-systole.

Stroke volume achieved by longitudinal pumping was calculated by multiplying AVPD with the short-axis area of the ventricle (SV_{long}) and longitudinal contribution to SV was determined by dividing SV_{long} with ventricular SV (LVSV_{long}%) as previously described (Carlsson *et al.*, 2007b; Steding-Ehrenborg *et al.*, 2013) Radial pumping was determined from the total heart volume variation (Carlsson *et al.*, 2007a).

Diastolic function measured as peak filling rate and systolic function measured as peak emptying rate of the left ventricle were calculated from the derivative of the time/volume curve (Maceira *et al.*, 2006a).

Invasive exercise measurements

Prior to the experimental days, elderly subjects completed an incremental (20w/min) cycling trial to exhaustion to determine peak workload. Young subjects were retrospectively enrolled and did not participate in invasive measurements.

For determination of indocyanine green (ICG; Pulsion Medical Systems, Germany) concentration, a 20 gauge catheter (Arrow, ES-14150, Reading, PA, USA) was inserted

percutaneously using the Seldinger technique into the right femoral artery, 2-5 cm below the inguinal ligament and advanced 8 cm in the proximal direction under local anaesthesia (2% Lidocaine). An 18 gauge venous catheter was inserted into an antebrachial vein of the left arm to inject ICG. A three-lead electrocardiogram was applied during catheterization and experimental procedures (Dialogue 2000, Danica, Copenhagen, Denmark), and the ECG and ICG were recorded simultaneously with the data-acquisition system (PowerLab, ADInstruments, Australia).

Exercise Protocol

After 30 min of supine rest, the subjects completed an incremental bicycle ergometer exercise test (Monark 839E or Monark 939 E, Vansbro, Sweden) until exhaustion. For elderly athletes and elderly sedentary exercise test started at 40-80W and workload was increased by 40-80W (i.e. 25, 50, 75 and 100% of the peak workload obtained in the initial cycling trial) every 3 min until exhaustion. For young sedentary, test protocols were based on age, weight and self-rated fitness level according to clinical practice. Protocols were chosen to yield exercise duration of ~8-12 min (Arena *et al.*, 2007). The test continued until exhaustion, i.e. until the subjects stopped due to fatigue or until they could not keep the pedalling rate above 60 rpm despite strong verbal encouragement. In all test, the respiratory exchange ratio at task failure was >1.15.

Systemic Oxygen Consumption

Oxygen uptake (VO_2) was measured continuously during exercise using an automated metabolic cart (Quark CPET system, Cosmed, Rome, Italy or Oxycon Champion, Jaeger, Hochberg, Germany). The instruments were calibrated with a 3L volume syringe and 2 gases

with varying [O₂] and [CO₂] prior to the experiment. Pulmonary gas measurements were averaged every 15 seconds (elderly) or 10 seconds (young).

Cardiac Output

A bolus (5-8 mg) of ICG was rapidly infused into the antebrachial vein followed by a 10 ml flush of saline while blood was continuously withdrawn (20mL/min) from the femoral artery by an automated pump (Harvard Apparatus, Millis, MA, USA) through a linear photodensitometer (Waters Instruments Inc., Rochester, MN, USA) and the voltage recordings were collected with the data-acquisition system. Withdrawn blood was re-infused into the left antebrachial vein in a closed-loop system. At the end of each experiment, a 3-point ICG-voltage calibration curve was derived from samples of the participant's blood and known volumes of ICG.

VO₂peak/THV ratio

The index VO₂peak (ml min⁻¹)/THV (ml) (Engblom *et al.*, 2010) was calculated and used to confirm or refute signs of heart failure in the population.

Statistical analysis

Statistical analysis was done using SPSS 20.0 (IBM, Chicago, IL, USA) and differences between groups were considered statistically significant when $p < 0.05$. Kruskal-wallis non-parametric test was used to identify variables where groups differed and Mann-Whitney non-parametric test was used to assess differences between groups. Linear regression analysis was performed to assess correlations between variables. In the elderly population stepwise multiple regression analysis was performed with maximal cardiac output (CO) as the independent variable and LVAVPD, THV, LVM and LVSVlong(%) were tested in the model.

Regression analysis was performed separately in both elderly and young subjects with VO_2peak as independent variable with THV, LVM, LVAVPD and LVSVlong(%) were tested as dependent variables. Values are presented as mean \pm SD unless stated otherwise.

Results

Subject characteristics are presented in Table 1.

Cardiac volumes

Ventricular and atrial volumes are presented in Table 2. Resting cardiac output and cardiac index (Cardiac index=CO/BSA) measured with Cardiac MR did not differ between groups (CO 6.0 ± 1.3 l min^{-1} for elderly athletes, 6.3 ± 1.5 l min^{-1} for elderly sedentary and 6.9 ± 1.1 for young sedentary, $p=0.27$, Cardiac index 3.1 ± 0.5 l m^{-2} , 3.2 ± 0.8 l m^{-2} and 3.5 ± 0.46 l m^{-2} , $p=0.24$ (Figure 2). At similar submaximal heart rates (119 ± 6 beats min^{-1}), CO was higher in elderly athletes (18.7 ± 3.3 l min^{-1}) than in sedentary elderly (13.6 ± 1.0 l min^{-1} ; $p=0.003$) Cardiac output during maximal exercise was 23.5 ± 3.3 l min^{-1} for elderly athletes ($n=8$) and 13.6 ± 2.4 l min^{-1} for elderly sedentary ($n=5$; $p=0.003$) and consequently also maximal cardiac index differed between groups (Figure 2). There was no difference in maximal heart rate reached during exercise between the active and sedentary elderly.

Longitudinal and radial pumping

Left ventricular AVPD was higher in elderly athletes and young sedentary compared to elderly sedentary (14 ± 3 mm, 15 ± 2 mm, and 11 ± 1 mm respectively, $p<0.05$). There was no difference between groups for RVAVPD (elderly athletes 20 ± 4 mm, young sedentary 21 ± 3 mm, elderly sedentary 18 ± 3 mm, $p=0.2$) (Figure 3A and B).

Left ventricular short-axis areas used for calculations of longitudinal pumping were smaller in young sedentary compared to both elderly groups ($54 \pm 12 \text{ cm}^2$ in elderly athletes, $46 \pm 3 \text{ cm}^2$ for elderly sedentary and $40 \pm 5 \text{ cm}^2$ for young sedentary ($p < 0.05$) whilst there was no significant difference between elderly groups ($p = 0.23$). Similarly, RV short-axis area was smaller in young sedentary compared to elderly (elderly athletes $52 \pm 9 \text{ cm}^2$, elderly sedentary $46 \pm 6 \text{ cm}^2$ and young sedentary $38 \pm 4 \text{ cm}^2$ ($p < 0.01$) whilst there was no difference between elderly ($p = 0.19$).

Left and right longitudinal contribution to SV did not differ between groups (LV $p = 0.12$, RV $p = 0.16$). For the LV, longitudinal contribution ranged between 52-65% in the whole population, and RV longitudinal was 77-87% (Table 2). Total heart volume variation (%), and thus radial contribution to SV was similar in all groups (elderly athletes $8.1 \pm 1.8\%$, elderly sedentary $8.6 \pm 1.4\%$ and young sedentary $7.9 \pm 2.8\%$, $p = 1.0$).

Furthermore, peak filling rate and peak emptying rate did not differ between groups (peak filling rate elderly athletes $516 \pm 138 \text{ ml s}^{-1}$, elderly sedentary $550 \pm 95 \text{ ml s}^{-1}$ and young sedentary $645 \pm 127 \text{ ml s}^{-1}$ $p = 0.26$ and peak emptying rate for elderly athletes $615 \pm 143 \text{ ml s}^{-1}$, elderly sedentary $670 \pm 104 \text{ ml s}^{-1}$, and young sedentary $715 \pm 148 \text{ ml s}^{-1}$ $p = 0.27$).

Determinants of cardiac output and oxygen uptake

In elderly subjects, LVAVPD was an independent predictor of maximal CO ($R^2 = 0.61$, $p < 0.01$, $\beta = 0.78$). Total heart volume, LVM and LVSVlong(%) did not add further value to the model. Total heart volume was an independent predictor of VO_2peak ($R^2 = 0.53$, $p < 0.01$, $\beta = 0.73$) and LVM, LVAVPD or LVSVlong(%) did not add to the model.

Total heart volume normalized for body surface area (THV/BSA) correlated to VO_2 peak ($\text{ml min}^{-1} \text{kg}^{-1}$) ($R^2=0.58$, $p=0.001$) and to maximal CO ($R^2=0.59$, $p<0.01$) (Figure 4A and B).

VO₂peak/THV ratio

The VO_2 peak/THV ratio as a measurement of normal cardiac function ranged between 2.5-3.6 in elderly athletes, 2.4-3.3 in elderly sedentary and 4.0-4.7 in young sedentary.

Discussion

The presented measurements of longitudinal and radial contributions to SV in this study provide novel insights to changes in heart function in elderly normal subjects and athletes. Against our hypothesis, there was no difference in longitudinal and radial contribution to SV between elderly athletes and elderly sedentary or between elderly and young sedentary. However, how the groups achieved their longitudinal pumping differed. The lower LVAVPD seen in elderly sedentary was compensated for by a larger short-axis area of the ventricle. As longitudinal pumping is calculated by multiplying AVPD with short-axis area, differences between groups were masked when only comparing longitudinal contribution to SV. This compensatory mechanism was previously shown in patients with heart failure by Carlsson *et al.* (Carlsson *et al.*, 2007b). The finding of the same compensatory mechanism in normal subjects raises important questions regarding the nature of healthy ageing. In the absence of regular physical activity, the sedentary group has developed a cardiac pumping mechanic that is considered pathological when found in combination with other symptoms of heart failure. Although beyond the scope of this study, this suggests that healthy ageing needs to include physical exercise to be considered truly healthy. However, it is important to note that there are no concerns that the untrained elderly population in the present study suffers from early

stage heart failure as their exercise capacity was within expected limits and the index of VO_{2peak}/THV that has been shown to discriminate between normal hearts and failing hearts was within normal range (Engblom *et al.*, 2010). Furthermore, results show that resting LVAVPD is an important predictor of a high cardiac output. Thus, lifelong endurance exercise preserves the function of the atrioventricular plane, enabling the heart to deliver large volumes of blood and preserve exercise capacity at levels similar to sedentary young subjects.

Cardiac pumping

The importance of maintained atrioventricular plane function can be understood through the mechanism of the hearts reciprocal filling and emptying. The movement of the atrioventricular plane is important not only for ejection of blood but also for filling of the atria (Hamilton & Rompf, 1932; Steding-Ehrenborg *et al.*, 2013). During ventricular systole the movement of the plane towards the apex of the heart causes pressure to drop in the atria and blood is aspirated into the atria from the caval and pulmonary veins (Steding-Ehrenborg *et al.*, 2013). Thus when the ventricle empty, the atria fill (Hamilton & Rompf, 1932). With reciprocal filling the heart maintains a constant volume (Bowman & Kovacs, 2003) which, according to the work by Lundbäck (Lundbäck, 1986), may save energy for the heart as no energy is lost to pulling on surrounding tissue.

The myofibres causing longitudinal pumping are complemented by oblique fibres that cause a circumferential rotational contraction of the left ventricle during systole (Streeter *et al.*, 1969). This rotational contraction known as the left ventricular twist is together with radial pumping highly important for maintained diastolic filling through the mechanism of diastolic suction (Rademakers *et al.*, 1992). The myofibres contain titin, a protein which acts like a spring that recoils back and untwists when the myocardium relaxes (Granzier & Labeit, 2004). This

causes a rapid drop in ventricular pressure and consequently inflow of blood from the atrium (Katz, 1930; Brecher, 1958; Courtois *et al.*, 1988). Nakai *et al.* (Nakai *et al.*, 2006) showed a close relationship between radial deformation and twisting, and furthermore investigated the effects of age in a cross-sectional study design of untrained young, middle aged and elderly subjects using two-dimensional speckle tracking echocardiographic imaging. Left ventricular diastolic untwisting was showed to decrease with increased age, which may be explained by the age related changes in heart rate and contractility (Dong *et al.*, 1999). With increased age, the ventricle becomes stiffer (Fujimoto *et al.*, 2012) which decreases contractility as well as relaxation and consequently diastolic suction, making the ventricle more dependent on atrial contraction for optimal filling.

Effects of long term exercise on cardiac pumping

To our knowledge, no previous study has investigated the effects of long term exercise on radial pumping. In the present study, there was no difference between groups for radial pumping at rest. However, Weiner *et al.* (Weiner *et al.*, 2010) performed a 90-day interventional exercise study on young male, relatively inexperienced athletes and showed improved twisting mechanics during systole as well as improved untwisting during diastole. Furthermore, ventricular twisting has been linked to preload and afterload, where increased preload increases twisting and increased afterload conversely causes a decrease in twisting (Dong *et al.*, 1999). As long term endurance training is known to increase blood volume and thus preload, as well as decrease blood pressure, thus decrease afterload, an increased ventricular twist can likely be found also in elderly athletes.

Cardiac pumping is also affected by ventricular compliance as adequate compliance is necessary to ensure appropriate filling of the ventricle at low filling pressures as well as allow

for increased ejection via the Frank-Starling mechanism (Arbab-Zadeh *et al.*, 2004). Arbab-Zadeh *et al.* (Arbab-Zadeh *et al.*, 2004) compared the effects of healthy sedentary ageing with life-long endurance training and showed that a sedentary lifestyle is associated with decreased compliance and diminished diastolic performance, whereas endurance training preserves compliance. The study by Arbab-Zadeh was performed on Master athletes who had been active for more than 20 years and that were now running on average 32 miles/week. Although it may not be necessary to train at the level of Master athletes, Bhella *et al.* (Bhella *et al.*, 2014) showed that 30 minutes of exercise, 4-5 days/week over a lifetime is needed to sufficiently prevent most of the decreases in left ventricular compliance with ageing.

The population of the present study did not show signs of stiff ventricles as there were no differences in radial contribution to SV (reflecting twisting mechanics as suggested by Nakai *et al.* (Nakai *et al.*, 2006)) or peak filling rate. However, these measurements were performed with Cardiac MR at rest and to fully establish differences in ventricular compliance cardiac catheterization is needed. During exercise, elderly athletes displayed a higher exercise capacity which was attributed to a preserved AVPD but may likely also be affected by a larger twisting reserve as well as better ventricular compliance.

The effects of exercise training on AVPD have previously been studied both at rest and exercise in young populations. Wisloff *et al.* (Wisloff *et al.*, 2001) assessed AVPD during exercise in young female cross-country skiers and found that AVPD fell significantly during exercise and concluded that AVPD is not an important mechanism for enhanced cardiac pumping during exercise. However, Slordahl *et al.* (Slordahl *et al.*, 2004) performed a short training study on sedentary young women lasting 8 weeks and found no change in AVPD at rest, however a significant increase in AVPD was seen during exercise at 85-90% of maximal

heart rate. Similar results were showed by Sundstedt et al. (Sundstedt *et al.*, 2008) in a study of young male endurance athletes where mitral AVPD increased from rest to peak exercise by 68% and 49% in the septal and lateral borders respectively. This is in line with the results of the present study of elderly subjects showing the importance of atrioventricular plane function during maximal exercise.

Chronic effects of training on AVPD has been shown by Carlhäll et al. (Carlhall *et al.*, 2001) where endurance trained young men had significantly higher mitral AVPD compared to untrained controls and strength trained athletes, and these results were supported by Steding-Ehrenborg et al. (Steding-Ehrenborg *et al.*, 2013) who showed larger left ventricular AVPD in male athletes compared to controls. In the present study, elderly athletes did not differ from young sedentary, but compared to age matched controls left ventricular AVPD was higher whereas there was no difference for the right ventricular AVPD. To the best of our knowledge, this is the first study to investigate AVPD in elderly athletes and further studies with a longitudinal design and including men and women of higher ages as well as testing both at rest and exercise are needed to fully establish the effects of exercise on AVPD and its importance for performance.

Left and right ventricular volumes and mass in the controls of the present study are comparable to previous studies of normal values for this age group (Hudsmith *et al.*, 2005; Maceira *et al.*, 2006a). Furthermore, total heart volumes, ventricular and atrial volumes in athletes were comparable to what has been shown in Cardiac MR studies of young athletes (Steding *et al.*, 2010; Mosen & Steding-Ehrenborg, 2014). When volumes where normalized to THV there were no differences between groups, which confirms that after lifelong

endurance training, athletes' heart is a physiologically enlarged heart where all four chambers have adapted in a balanced way.

Limitations

Two different MR-scanner were used in this study. However, as both scanners had field strength of 1.5T and comparable sequences were used for image acquisition this has likely not affected the results. Furthermore, the study population of elderly subjects was small and a larger sample size would have strengthened the results for invasive measurements. However, for MR-parameters normalized for body surface area, the study population is large enough to achieve a calculated power of 82%. Young subjects were retrospectively enrolled and did not undergo invasive measurements of cardiac output and it is therefore not possible to conclude what variable is the main determinant of maximal CO in this group.

Conclusion

This study compares novel quantitative measurements of longitudinal and radial function between elderly with lifelong experience of endurance training, healthy sedentary elderly and young sedentary subjects. Longitudinal and radial contribution to SV did not differ between groups. However, how longitudinal pumping was achieved differed between elderly athletes and young subjects compared to elderly sedentary. Elderly athletes and young sedentary showed a similar AVPD whilst it was significantly lower in elderly sedentary subjects. Instead, elderly sedentary compensated for decreased AVPD with increased short-axis area of the ventricle. Furthermore, left resting ventricular AVPD was shown to be an independent predictor of maximal cardiac output.

Acknowledgements

The authors would like to acknowledge Professor Bengt Saltin who conceptualized the MR study, provided financial support, assisted in data collection and analysis and revised the early drafts of the manuscript. He sadly passed before the manuscript reached its final stages. We also thank Lars G. Hanson at Hvidovre Hospital, Denmark, Jaya Rosenmeier at Copenhagen University Hospital, Denmark and Ann-Helen Arvidsson and Christel Carlander, Skåne University Hospital Lund, Sweden, for assistance in data-collection and administrative tasks.

Funding

This study was supported by grants provided to Prof. Bengt Saltin by the Novo Nordisk Foundation. KSE was funded by a post-doc scholarship from the Swedish Heart Association. The research on young healthy subjects was part of a larger study funded by the Swedish Research Council, the Swedish National Centre for Research in Sports, the Swedish Heart and Lung Foundation, the Medical Faculty at Lund University, Sweden and the Region of Scania, Sweden.

Competing interest

The authors have no competing interests to declare.

Author contribution

KSE and SM conceptualized the study. KSE and PA collected MR-data and KSE analysed the images. SM, JAC and RB collected and analysed data from exercise tests and CO-measurements. KSE, SM and RB drafted the manuscript. All authors have read and critically revised the final version of the manuscript.

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Figure legends

Figure 1. Example of delineations for total heart volume in short-axis slices. All structures within the pericardial sac were included in the total heart volume; left and right ventricle, left and right atria, aortic and pulmonary trunk. *Ao = Aorta, Pulm = Pulmonary artery, LV = left ventricle, RV = right ventricle, LA = left atria, RA = right atria.*

Figure 2. Cardiac index (CI) at rest and exercise in athletes and sedentary. There was no difference between groups at rest. However during maximal exercise, CI was significantly higher in elderly athletes. Measurements at rest were performed using non-invasive Cardiac MR, and at maximal exercise using the invasive dye dilution technique.

Figure 3. Left and right atrio-ventricular plane displacement (AVPD) in elderly athletes, elderly sedentary and young sedentary. Elderly athletes had a preserved LVAVPD similar to what is seen in young sedentary, whilst elderly sedentary had decreased LVAVPD. There was no difference between groups for RVAVPD.

Figure 4. Panel A: The relationship between total heart volumes normalized for body surface area (THV/BSA) and peak oxygen uptake ($\text{VO}_{2\text{peak}}$, $\text{ml min}^{-1} \text{kg}^{-1}$). **Panel B:** The relationship between THV/BSA and maximal cardiac output (CO max) determined by dye dilution technique. Only elderly subjects underwent invasive examinations and are included in the figures.

Tables

Table 1. Subject characteristics.

	Elderly Athletes N = 8	Elderly Sedentary N = 7	Young Sedentary N=10
Age (years)	64±4	66±4	29±4
Weight (kg)	74±8	80±7	78±8
Height (cm)	179±7	175±10	179±3
BSA (m ²)	1.91±0.15	1.98±0.11	1.95±0.12
SBP (mmHg)	139±13	145±6	126±6
DBP (mmHg)	76±10	73±12	75±4
VO ₂ peak (ml min ⁻¹ kg ⁻¹)	42±9	28±7	44±6
VO ₂ peak (l*min ⁻¹)	3.0±0.7	2.3±0.4	3.0±0.7

BSA – body surface area, DBP – diastolic blood pressure, SBP – systolic blood pressure,

VO₂peak – peak oxygen uptake

Table 2. Cardiac volumes and mass determined from Cardiac MR.

	Trained N = 8	Untrained N = 7	Young Untrained N=10
THV (ml)	1040±237	806±129	783±90
LVEDV (ml)	212±51	160±24	183±23
LVSV (ml)	119±31	99±19	107±17
LVM (g)	151±36	115±12	120±19
RVEDV (ml)	225±58	180±32	219±27
RVSV (ml)	118±30	97±15	103±15
LAm _{ax} (ml)	123±35	90±23	77±19
RAm _{ax} (ml)	129±34	101±25	110±18
LVSV _{long} (%)	65±13	52±9	55±5
RVSV _{long} (%)	87±13	78±11	77±7
LVM/THV (g/ml)	0.15±0.01	0.14±0.01	0.15±0.02
LVEDV/THV	0.20±0.01	0.20±0.01	0.23±0.01
RVEDV/THV	0.22±0.02	0.22±0.03	0.28±0.02
LAm _{ax} /THV	0.12±0.01	0.11±0.02	0.10±0.02
RAm _{ax} /THV	0.14±0.02	0.12±0.02	0.14±0.01
THV/BSA (ml/m ²)	540±98	409±72	401±35
LVM/BSA (ml/m ²)	78±15	59±7	61±8
LVEDV/BSA (ml/m ²)	110±21	81±14	94±10
RVEDV/BSA (ml/m ²)	116±24	91±21	112±2
LAm _{ax} /BSA (ml/m ²)	64±16	46±14	39±8
RAm _{ax} /BSA (ml/m ²)	72±15	52±15	56±9

BSA – body surface area, LA – left atrium, LVEDV – left ventricular end-diastolic volume, LVM – left ventricular mass, LVSV – left ventricular stroke volume, LVSVlong – longitudinal contribution to left ventricular stroke volume, RA – right atrium, RVEDV – right ventricular end-diastolic volume, RVSV – right ventricular stroke volume, RVSVlong - longitudinal contribution to right ventricular stroke volume, THV – total heart volume.

Figures

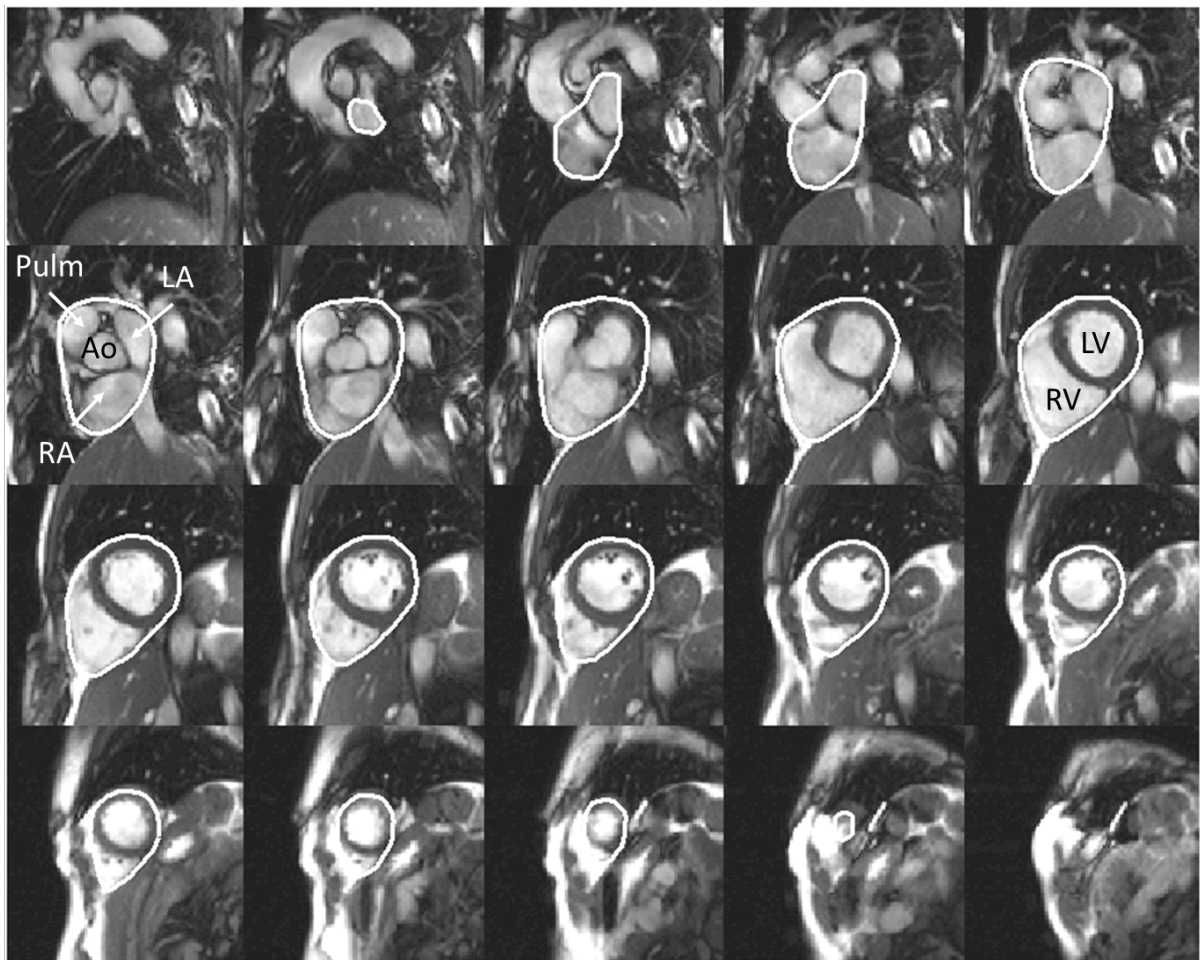


Figure 1.

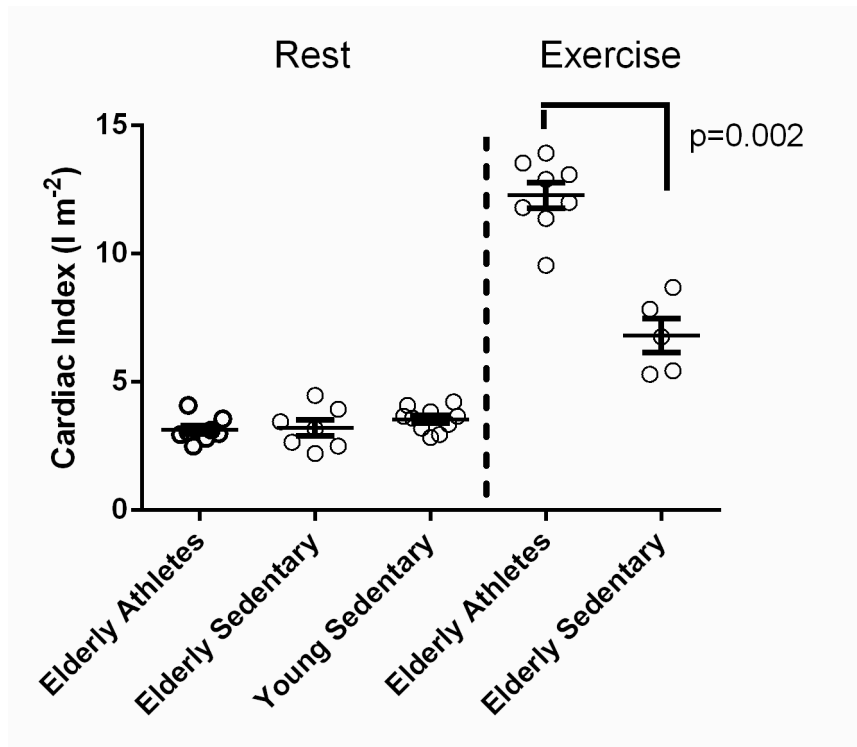


Figure 2.

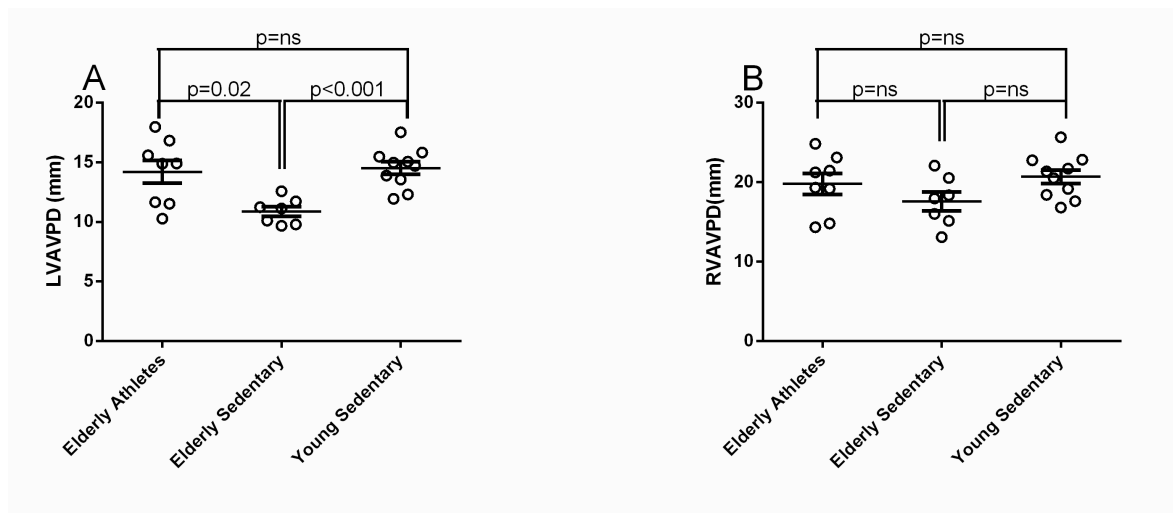


Figure 3.

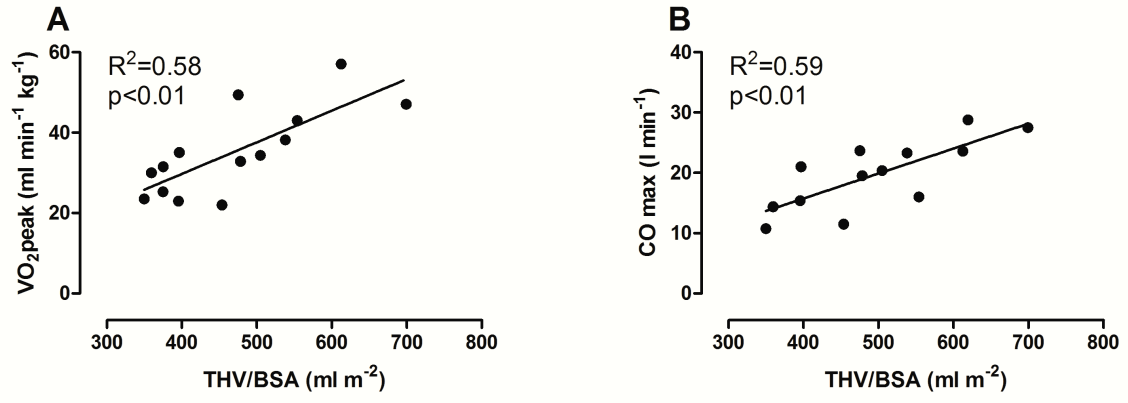


Figure 4.