Ultrasound / White paper

The “modern-day stethoscope” unravelling the mystery of the “athlete’s heart”

Synchronising exercise and cardiac assessments in the paediatric athlete

Curtis Wadey MSc (photo), Prof. Guido E. Pieles, Prof. Craig A. Williams
The Children’s Health and Exercise Research Centre (CHERC)
Faculty of Health and Life Sciences
University of Exeter
Exeter, UK

Introduction

The unique physiological adaptation of athletic training has fascinated researchers and the public alike for many centuries (Castelletti and Pieles, 2022). Recent advances in medical and imaging technology are enabling researchers to investigate cardiac function during exercise, gaining novel insights in the athletic heart using cardiac exercise magnetic resonance imaging (La Gerche et al., 2013; Pieles et al., 2014) and echocardiography (Claessen et al., 2016; Pieles et al., 2020). Cardiac adaptation is however only one of the many organ systems that determine exercise capacity and training response. A comprehensive assessment of exercise physiology therefore is paramount and “Cardiopulmonary exercise testing (CPET)” is the gold standard assessment of an individual’s cardiorespiratory fitness. CPET can unmask pathologies not normally seen during a resting examination such as ventilatory patterns and cardiac arrhythmias. CPET usually involves exercise by the participant running or cycling on an ergometer to their maximum effort, at the same time their heart rate/rhythm, blood pressure, power output, and pulmonary gases are recorded. However, a limitation of CPET is that it only provides an indirect quantification of cardiac function. This can be overcome if echocardiographic monitoring is added during the test.

Echocardiography can be acquired feasibly during exercise and advances in Wall Motion Tracking (WMT) strain echocardiography may also increase sensitivity and specificity in identifying subtle changes in cardiac function, which may indicate an underlying pathology (Pieles et al., 2020). Using WMT, we measure the amount of strain in a specific point of myocardium during a cycle, which makes it one of the best non-invasive measures of cardiac performance. Longitudinal and circumferential strain (Sc) and circumferential strain rate (SRc) can be measured from apical and parasternal short axis views of the heart respectively, which can be obtained comfortably for a sonographer when the participant is on a recumbent cycle ergometer. Furthermore, WMT is less load and angle dependent than other techniques, which makes it the appropriate choice for imaging during exercise. By pairing both CPET and innovative echocardiographic techniques such as WMT provided by Canon, it allows the clinician/researcher to simultaneously measure cardiac, pulmonary, metabolic, and muscular responses to exercise. We aim to describe here the combined and integrated data that can be collected from a visit to the exercise laboratory in a single exercise test and highlight potential areas for future research and development.

Methods

Participant

The data presented is from an elite 14-year-old male academy football player in the United Kingdom. There was no evidence of underlying cardiac disease following standard cardiac screening protocols.

Echocardiography

The participant received a resting scan and exercise echocardiography by an expert paediatric sports cardiologist (GEP), using a Canon Aplio i900 system, with a PSI-30BX (i6SX1, 1.5-6.0 MHz) transducer and Vitrea for ultrasound (V7.11) software (Canon Medical Systems, Japan). Parasternal short axis view and apical four-chamber views were captured for strain analysis. Left ventricle (LV) global longitudinal (Sl) and circumferential (Sc) peak systolic strains were defined as the maximal deformation value of a segment during systole in the endocardial segment and is represented as a percentage (%). Global strain rate index (SRI and SRc) was defined as the rate of deformation of a segment in systole over time and is expressed in 1/s.

Exercise protocol

The exercise protocol combined CPET with simultaneous echocardiography on a recumbent cycle ergometer (Ergosana, Germany). Every three minutes the resistance cycled against increased (50 W • 3 min^{-1}), with the aim of getting the participant to reach maximal exhaustion in 10 to 15 minutes. At the end of each step blood pressure and perceived exertion were recorded. The electrocardiogram and gas exchange were continuously monitored. Echocardiography was performed at rest, during exercise at 0, 50, 100, 150 W, and two and six minutes post exercise. This protocol has been previously described by Pieles et al. (2015, 2020).

Results

All conventional echocardiography parameters and exercise test responses were considered normal. The participant had a stature of 180 cm, a body mass of 67.4 kg, an estimated fat free mass of 53.9 kg, and he was past his highest rate of adolescent growth (known as peak height velocity). The cardiopulmonary, blood pressure, and cardiac responses to the CPET and have been summarised in Figures 1 and 2, respectively. Figure 1 displays the participant's heart rate (panels 2 & 5), ventilatory (panels 1, 4, 6-7), and metabolic responses (panels 3, 5, 6, 8-9) during exercise and recovery. These responses can be compared to healthy responses to assess if there are any cardiac, respiratory, or metabolic limitations present. In this example, the participant achieved a peak power output of 300 watts, a peak heart rate (HR) of 198 b·min^{-1}, a minute ventilation (V_E) of 143 L·min^{-1}, a peak oxygen consumption (peak VO_2) of 3.28 L·min^{-1}, a relative peak VO_2 to body mass of 48.7 mL·kg^{-1}·min^{-1}, a respiratory exchange ratio (RER) of 1.24 (Fig. 1). The participant's gas exchange threshold (GET), a surrogate for anaerobic threshold occurred at a VO_2 of 1.95 L·min^{-1}, which corresponds to ~60% of the peak value. Figure 2 displays cardiac performance as a function of different metrics of exercise intensity (e.g., power output, VO_2, HR, oxygen pulse, and blood pressure). Longitudinal strain (Sl) and longitudinal strain rate (SRl) had a resting value of -21.2% and -1.11 1/s respectively and increased progressively throughout exercise to -25.4% and -2.24 1/s at 150 W. Sl appears sensitive to exercise with an almost immediate increase in strain from rest to 0 W. Sl and SRI return to near baseline values at two minutes and six minutes post-exercise (Fig. 3). Circumferential strain (Sc) and circumferential strain rate (SRc) resting values were -31.8% and -1.7 1/s, and remained stable until 100 W. At 150 W Sc and SRc increased to -37.7% and -3.4 1/s and continued to increase into recovery up to a peak of -38.3% and -3.9 1/s at two minutes post-exercise (Fig. 4).

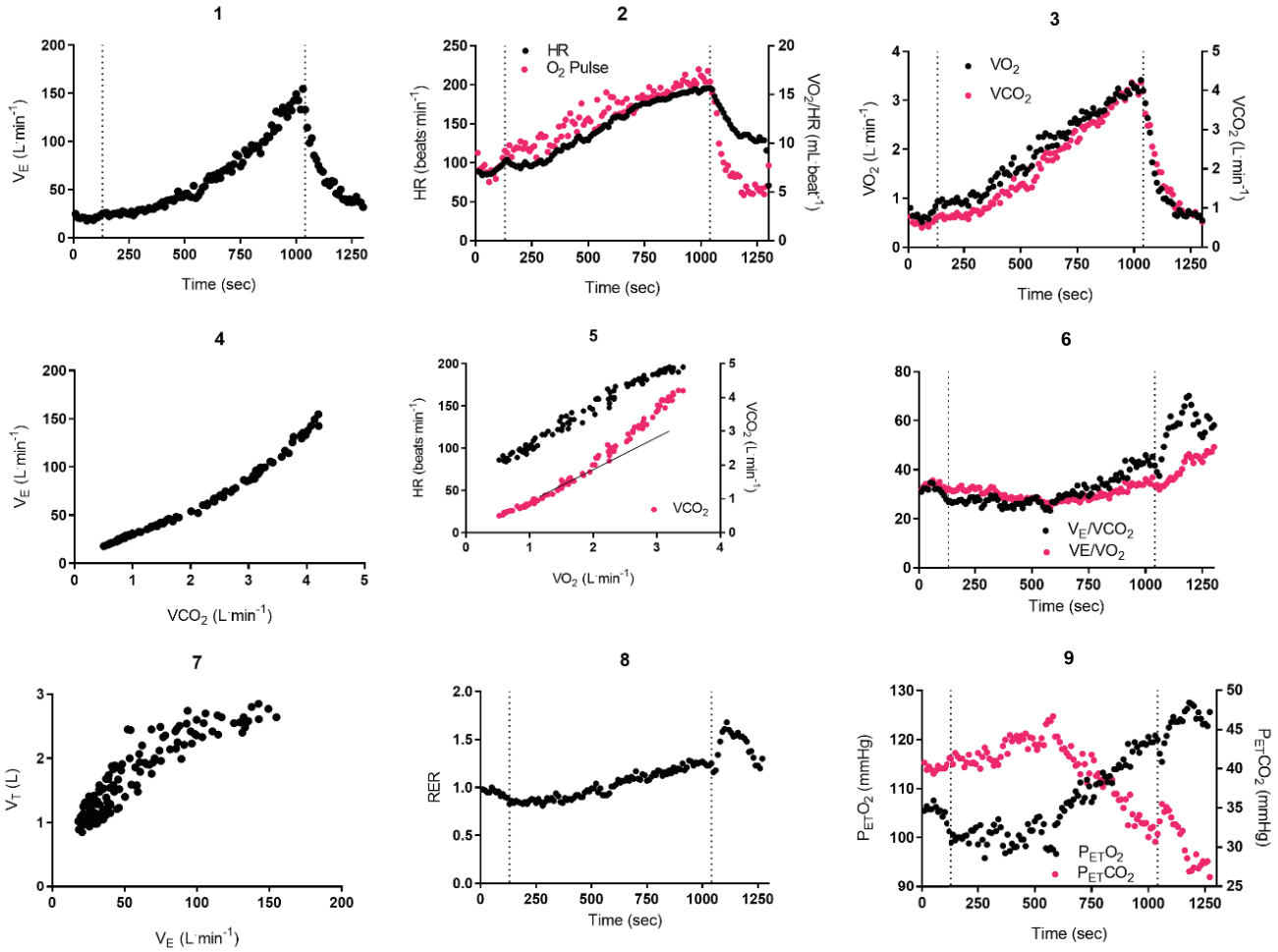

Figure 1 Cardiopulmonary responses to exercise (the vertical dotted lines represent the start and end of the exercise).
V_T, tidal volume; V_E, minute ventilation; $P_{ET}O_2$, end tidal oxygen; $P_{ET}CO_2$, end tidal carbon dioxide; VO_2, volume of oxygen; VCO_2, volume of carbon dioxide; HR, heart rate; RER, respiratory exchange ratio.

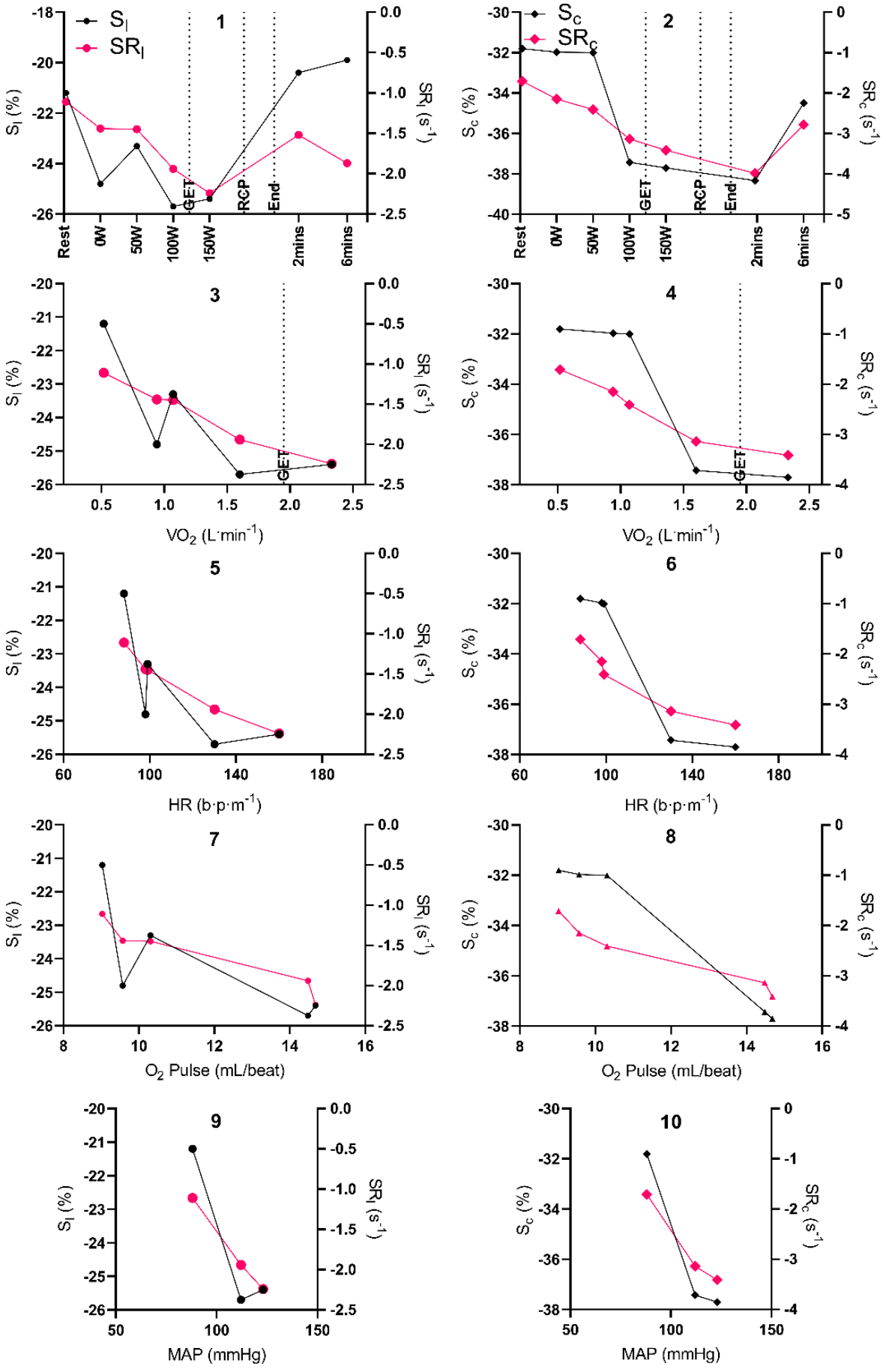

Figure 2 Cardiac responses as a function of exercise intensity and physiological responses.
SI, longitudinal strain; SRI, longitudinal strain rate; GSc, circumferential strain; GSRc, circumferential strain rate; GET, gas exchange threshold; RCP, respiratory compensation point; VO_2, volume of oxygen; HR, heart rate; MAP, mean arterial pressure.

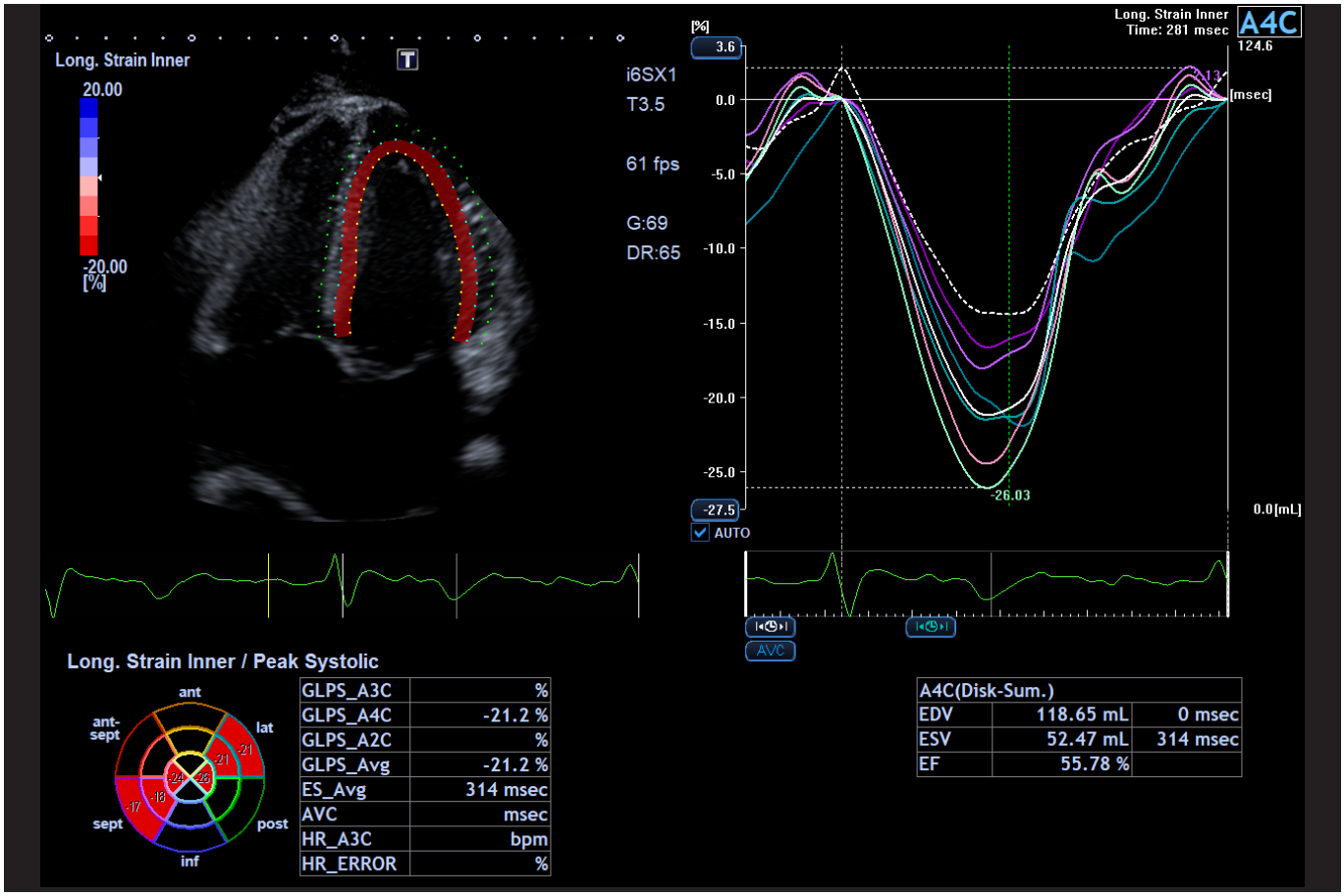

Figure 3 Resting LV longitudinal strain analysis of the apical four chamber view using Canon Vitrea for ultrasound (V7.11) software.

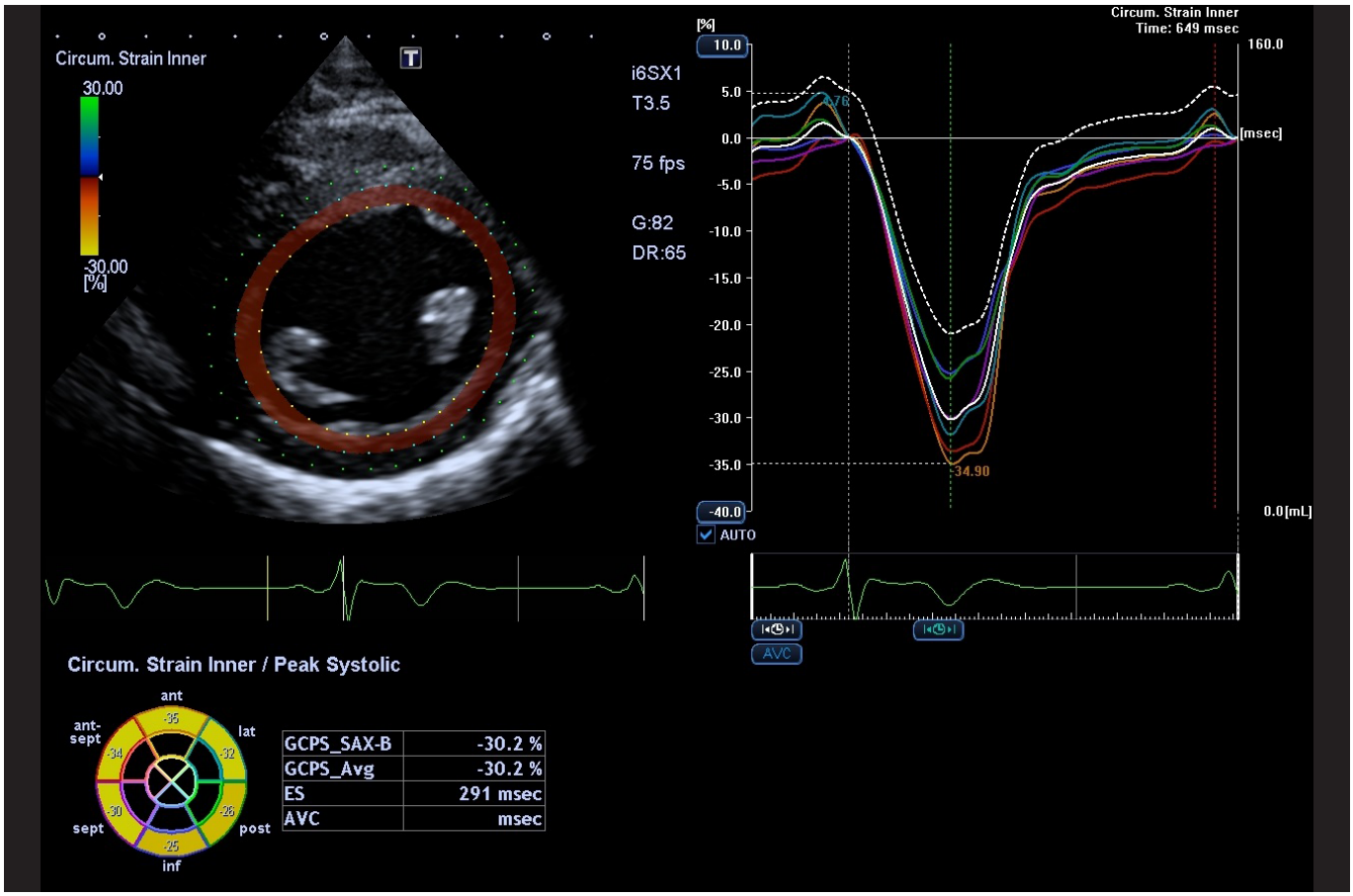

Figure 4 Resting LV circumferential strain analysis of short axis base view using Vitrea for ultrasound (V7.11) software.

Discussion

Figures 1 and 2 summarise the additional information that can be captured by completing one exercise echocardiography test, which takes approximately 20 minutes. A 9-panel plot displays the participant's cardiopulmonary responses to the CPET, in which his ventilatory patterns and thresholds can be visualised (Fig. 1). Panels 4-6 allow for an in-depth analysis into that participant's respiratory landmarks, such as the GET or "anaerobic threshold" and respiratory compensation point (RCP). These thresholds allow the clinician/researcher to see the participant's metabolic state transition from aerobic to predominately anaerobic metabolism.

Being able to non-invasively determine the participant's metabolic state and utilise WMT is cutting-edge and allows researchers to unravel some mystery of the athlete's heart. For example, in this case study as the exercise starts the participant's SI strain preferentially increases, then at higher intensity (~100 W) Sc increases predominantly to increase global myocardial performance. At end exercise V_E, VO_2 and HR fall drastically (Fig. 1), and cardiac parameters SI and SRI also return to near baseline levels two minutes post exercise. Interestingly, Sc and SRc continue to increase after exercise and up to their peak at two minutes post exercise. It could be postulated that after exercise has ended with the subsequent fall in HR, to maintain stroke volume/cardiac output, Sc continues to increase to maintain stroke volume (and thereby cardiac output) to repay the oxygen debt accumulated by the working skeletal musculature. Our methodology also confirms the relationship between oxygen (O_2) pulse and cardiac function during exercise, O_2 pulse is clinically used as an indirect measure of cardiac function and, Figure 2 shows the simultaneous increase between LV strain and O_2 pulse. Understanding these intricate myocardial mechanics during exercise will help researchers decipher the workings of the athlete's heart. WMT may also hold the key to being able to discriminate between normal physiological adaptations to exercise training compared to early signs of myocardial disease (e.g., cardiomyopathies) (Dorobantu et al., 2022; Pieles et al., 2019). A current limitation of this method is that of the seven exercise stages the participant completed (0 to 300 W), strain could only be recorded for the first five (rest to 150 W) due to the participant's ventilation (evidenced by a peak V_E of >140 $L{\cdot}min^{-1}$) and chest wall movement. As ventilation rises it becomes increasingly more challenging to capture a full cardiac cycle in between breaths. Additionally, data acquisition at highest HR remains challenging, although recent technological advances allow frame rates per second (FPS) during image acquisition of up to 100 fps, hence allowing data analysis with good intra- and inter-observer variability even at HR of 150 bpm (Pieles 2020). Overall, the exercise echocardiography protocol does allow the clinician/researcher to simultaneously assess cardiac and metabolic responses to exercise, which are currently not seen in traditional cardiac screening at rest.

Conclusion

The additional information that can be provided by a single exercise echocardiography study in the future may be able to improve the sensitivity and specificity of cardiac screening in healthy young athletes. Exercise echocardiography provides a dynamic and direct evaluation of respiratory and myocardial performance, which can unmask early and discrete cardiac pathology. Future work will be aimed at refining the protocol including the number and duration of stages required, applying these techniques to clinical populations (such as congenital heart disease), and improving the diagnostic and prognostic yield from long-term follow up.

References

1. Castelletti S, Pieles GE (2022). The athlete's heart from Philippides to the modern marathon runners. *European Heart Journal*, 2538–2541.
2. Claessen G, La Gerche A, Voigt JU, Dymarkowski S, Schnell F, Petit T, Willems R, Claus P, Delcroix M, Heidbuchel H (2016). Accuracy of Echocardiography to Evaluate Pulmonary Vascular and RV Function during Exercise. *JACC: Cardiovascular Imaging*, 9(5), 532–543.
3. Dorobantu DM, Radulescu CR, Riding N, McClean G, de la Garza MS, Abuli-Lluch M, Duarte N, Adamuz MC, Ryding D, Perry D, McNally S, Stuart AG, Sitges M, Oxborough, DL, Wilson M, Williams CA, Pieles, GE (2022). The use of 2-D speckle tracking echocardiography in assessing adolescent athletes with left ventricular hypertrabeculation meeting the criteria for left ventricular non-compaction cardiomyopathy. *International Journal of Cardiology, October.*
4. La Gerche A, Claessen G, Van De Bruaene A, Pattyn N, Van Cleemput J, Gewillig M, Bogaert J, Dymarkowski S, Claus P, Heidbuchel H. (2013). Cardiac MRI: A new gold standard for ventricular volume quantification during high-intensity exercise. *Circulation: Cardiovascular Imaging*, 6(2), 329–338.
5. Pieles GE, Gowing L, Forsey J, Ramanujam P, Miller F, Stuart AG, Williams CA (2015). The relationship between biventricular myocardial performance and metabolic parameters during incremental exercise and recovery in healthy adolescents.*American Journal of Physiology - Heart and Circulatory Physiology*, 309(12), H2067–H2076.
6. Pieles GE, Gowing L, Ryding D, Perry D, McNally SR, Stuart AG, Williams CA (2020). Characterisation of LV myocardial exercise function by 2-D strain deformation imaging in elite adolescent footballers. *European Journal of Applied Physiology*, 121(1), 239-250.
7. Pieles GE, Grosse-Wortmann L, Hader M, Fatah M, Chungsomprasong P, Slorach C, Hui W, Fan CPS, Manlhiot C, Mertens L, Hamilton R, Friedberg MK (2019). Association of echocardiographic parameters of right ventricular remodeling and myocardial performance with modified task force criteria in adolescents with arrhythmogenic right ventricular cardiomyopathy. *Circulation: Cardiovascular Imaging*, 12(4), 1–11.
8. Pieles GE, Szantho G, Rodrigues JCL, Lawton CB, Stuart AG, Bucciarelli-Ducci C, Turner MS, Williams CA, Tulloh RMR, Hamilton MCK (2014). Adaptations of aortic and pulmonary artery flow parameters measured by phase-contrast magnetic resonance angiography during supine aerobic exercise. *European Journal of Applied Physiology*, 114(5), 1013–1023.

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