

Tissue Velocity Imaging for Monitoring of Muscle Function in Circulatory Assist Systems

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Abstract

In a series of studies we tested potential applications of tissue velocity imaging (TVI) for pre-surgical and post-surgical assessment in skeletal muscle circulatory assist systems. TVI is an ultrasound modality which is capable of measuring velocities within solid tissues such as skeletal muscle. An initial evaluation in healthy volunteers demonstrated that TVI can characterise the rapid phases of *in-situ* skeletal muscle contraction with high temporal and spatial resolution. In the clinical setting of cardiomyoplasty TVI provides information about electromechanical relationships in the stimulated myograft, and the effect of changes in stimulator settings on ventricular wall motion. These measurements may help optimize myograft stimulation in clinical practice. Finally, preliminary results show that TVI is capable of imaging skeletal muscle ventricle wall motion, and this application is the subject of more detailed evaluation. TVI is a useful non-invasive modality for the monitoring of skeletal muscle function in cardiac assist systems.

Key words: cardiomyoplasty, skeletal muscle, skeletal muscle ventricles, Doppler ultrasound.

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Monitoring of skeletal muscle graft function is pivotal to the development and clinical application of skeletal muscle cardiac assist systems. In dynamic cardiomyoplasty, non-invasive monitoring of myograft function is rendered difficult by the intrathoracic location of the latissimus dorsi muscle [2]. As a result, methods of monitoring the myograft have until recently been sub optimal. Palpation of latissimus dorsi impulse in the axilla is a qualitative assessment which is influenced by the patient's build, and which can only reflect function of the proximal and least vulnerable portion of the muscle [3]. Fluoroscopy has also been applied to this problem, using the muscle electrodes as markers. Theoretically, this can provide a quantitative measurement of contraction of the muscle between these markers, but the technique has not yet been evaluated systematically and involves exposure to ionising radiation which makes serial assessments impractical. Left ventricular angiocardiology can give a quantitative assessment of left ventricular ejection, but is not applicable for repeated clinical assessments [1].

M-mode echocardiography is widely used to determine synchronization settings in cardiomyoplasty. It is well established that initiation of myograft contraction before mitral valve closure has a negative effect on symptoms and hemodynamics [9,13]. However, the widely adopted practice of initiation of myostimulation at the moment of mitral

valve closure has not been clinically validated. B-mode ultrasound provides some information about left ventricular geometry without quantifying myograft function or its effect on ventricular wall contraction force. The ideal monitoring modality for monitoring in skeletal muscle assist systems should have the following characteristics:

- non-invasive
- portable
- radiation-free
- provides a quantitative assessment of function of the graft and its effect on left ventricular wall dynamics
- applicable to experimental models of skeletal muscle circulatory support.

Tissue Velocity Imaging - Basics

Tissue velocity imaging (TVI) is a variant of color Doppler imaging which utilises specific filtering and amplification hardware to encode the Doppler information from moving tissues [14]. Whereas Doppler blood flow imaging requires high-gain amplification of a weak, high velocity signal (blood flow velocities are typically in the range 30-200 cm/sec), TVI filters out these high velocity signals whilst preserving signals in the range 0-30 cm/sec. In addition, the reflected signal from solid tissue has a greater amplitude than that of the blood pool and lower gain amplification is required before demodulation of the Doppler signal [7]. Two systems are now commercially avail-

able which use these principles to measure myocardial contraction (Doppler Tissue Imaging [DTI] - Acuson, Mountain View, California; Tissue Doppler Imaging [TDI] - Toshiba, Tustin, California). Three modalities of TVI can be used to assess tissue motion. Two-dimensional TVI allows a velocity map to be created of a two-dimensional region of interest, with a frame rate governed by the size of this region. This is useful for identifying structures prior to quantitative analysis. M-mode TVI allows study of these regions with much greater temporal resolution (intervals as small as 0.02 second can be studied). These images can be analysed off-line to measure the mean velocity across a region of interest. This method is the basis for the studies shown below. Finally, pulsed Doppler TVI allows high-resolution quantitative analysis to be made of tissue within a given sample volume.

In-Situ Skeletal Muscle Assessment

During the development of TVI for clinical applications, it was noted that contraction of forearm muscle groups could be measured [14]. This observation was followed up in a study of limb muscle contraction in healthy volunteers [10]. In that study, active contraction and passive limb movements were compared, and TVI was found to be capable of differentiating these two movements in terms of the intramuscular velocity-time characteristics. Furthermore, isometric and isotonic muscle contraction characteristics were readily identified using TVI, and the temporal resolution of the TVI system was such that muscle tetany and the rapid phases of a tendon jerk reflex could be identified. Unpublished data from our center also show that TVI is capable of resolving contraction characteristics of superficial muscle groups such as latissimus dorsi, although image resolution was limited by the use of a 4Mhz transducer which is not optimal for this application (figure 1). Further development of TVI software for higher frequency transducers should allow more detailed studies of latissimus dorsi muscle for pre-training and pre-surgery assessment.

TVI Assessment after Dynamic Cardiomyoplasty

TVI has now been shown to have useful clinical application for assessing both myograft function and ventricular wall motion in dynamic cardiomyoplasty. In a limited study of seven patients after cardiomyoplasty, we assessed the proximal and mid sections of the latissimus dorsi myograft using new ultrasound windows [11]. The proximal part of the myograft was examined by positioning the transducer over the medial axillary wall with 45 degree cranial angulation, angled into the window of the resected second rib (termed "axillary view"). The intrathoracic part of the free myograft was examined in the mid axillary line, fourth intercostal space with cranial angulation (termed "thoracic view"). A limitation of this method of examining the myograft is that contraction velocities are underestimated because of the angle of incidence between the transducer and the axis of muscle contraction. This renders

inter-patient comparisons difficult to interpret, but within individual patients relative changes in muscle velocity can be examined, provided that the angle of insonation is kept constant.

In our original study, we demonstrated that TVI provides sufficient temporal resolution to show details of the relationship between the burst stimulus and the contraction-relaxation profile of the free latissimus dorsi muscle even with a single pulse stimulus (figure 2). Using a standard 6 pulse burst at 33 Hz, the highest graft velocities are seen within the first 100 ms of the burst. Muscle shortening continued for a further 100 ms after completion of the (150 ms) burst stimulus. Myograft relaxation took up to 400 ms in some subjects. Thus, the contraction-relaxation cycle can take up to 650 ms, theoretically long enough to cause restriction to cardiac filling with heart rates as low as 90 beats per minute. In two subjects, muscle failure was identified by examining free latissimus dorsi muscle. In these subjects, low velocities were seen in the muscle both during assisted and non-assisted cycles because of passive motion imparted by cardiac contraction.

TVI was also used in that study to assess ventricular wall motion during assisted and unassisted cycles (figure 3). Using TVI M-mode imaging uploaded into a digital image acquisition system (Prism 2000, Freeland Systems, Denver, Colo), we calculated mean intramural velocities for the posterior wall of the left ventricle during assisted and non-assisted cycles. These can be plotted as wall velocity-time graphs, and the velocity increase during assisted cycles can be calculated from these. This value is termed the assist velocity difference (AVD). Augmentation of posterior wall motion was defined by the difference between peak assisted cycle and non-assisted cycle velocities. Among the patients who were shown to have good myograft function from TVI imaging of free latissimus dorsi, a sigmoid relationship was found between the pulse amplitude and the AVD. The points of inflexion of this relationship varied between patients, suggesting that TVI could be used to tailor device settings to the individual. It is noteworthy that not all of the increase in posterior wall velocity represents augmentation, since contraction of the free latissimus dorsi muscle also causes cardiac displacement. Displacement can account for up to 25 percent of the apparent augmentation measured using this technique [12].

TVI Assessment of Skeletal Muscle Ventricles

The use of skeletal muscle for circulatory assistance has been mainly limited in its clinical application to dynamic cardiomyoplasty. In experimental models, skeletal muscle has also been used to create new pump chambers, or skeletal muscle ventricles. These are being developed with a view to application as counterpulsators or ventricle replacements. Long-term studies of skeletal muscle ventricle performance are limited by the practical difficulties associated with repeated invasive hemodynamic measurement. Preliminary data from a collaboration between the University of Edinburgh and Manchester University, UK, show that

TVI can be used to quantify SMV wall velocity (figure 4) [8]. The full results of a study which evaluated TVI indices of SMV function against invasive measurements of pressure and flow generation will be published next year.

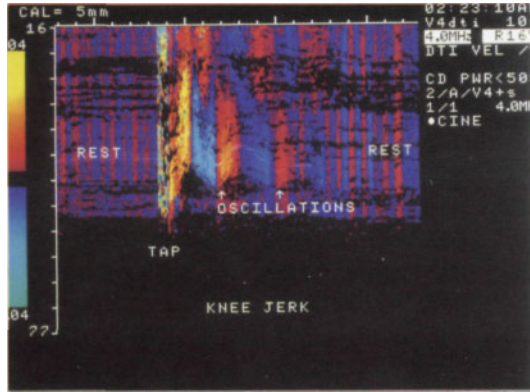


Figure 1. Tissue velocity imaging M-mode tracing quadriceps contraction in a healthy volunteer (hiring a knee jerk reflex). The velocity scale is shown on the left of the figure. The initial mechanical impulse ('TAP') of the tendon hammer is followed rapidly by muscle contraction (yellow) with the direction of shortening toward the transducer. This is followed by two oscillations, the second of which is of lower velocity. (X-axis = time; one tick = 0.2 seconds. Y-axis = tissue depth; one tick = 5 millimeters. Color scale: Red/yellow coloration represents motion towards the transducer, blue/green represents motion away from the transducer. Velocities are metres/second).

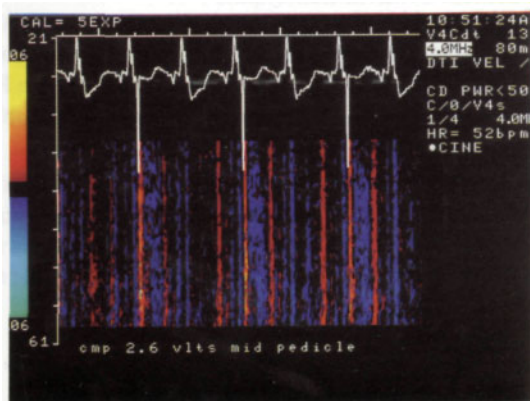


Figure 2. Tissue velocity imaging of unconditioned latissimus dorsi from the thoracic view. A single 2.6 Volt stimulus is applied on alternate cycles. Muscle twitch (red) is clearly seen associated with the myostimulation spike. (X-axis = time; one tick = 0.2 seconds. Y-axis = tissue depth; one tick = 5 millimeters. Color scale: Red/yellow coloration represents motion towards the transducer, blue/green represents motion away from the transducer. Velocities are metres/second).

Future Perspectives

TVI provides a means by which myograft contraction profile can be assessed both in the clinical and experimental setting. More sophisticated stimulation regimes are

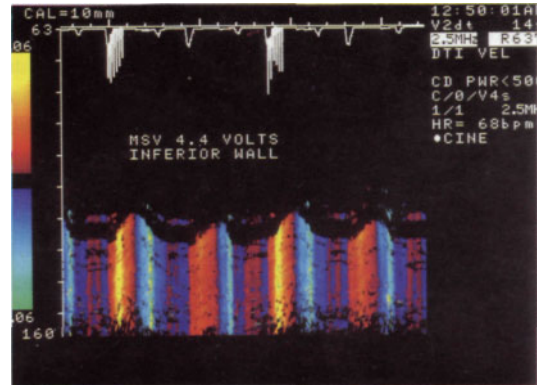


Figure 3. Doppler tissue imaging M-mode tracings of the left ventricular inferior wall in a patient after cardiomyoplasty, with muscle stimulation voltages of 4.4 V. The first and third cycles are assisted (hurst stimulus on EKG). Note the markedly increased posterior wall systolic velocity during cardiac assist, denoted by bright yellow color coding. (X-axis = time; one tick = 0.2 seconds. Y-axis = tissue depth; one tick = 10 millimeters. Color scale: Red/yellow coloration represents motion towards the transducer, blue/green represents motion away from the transducer. Velocities are metres/second).

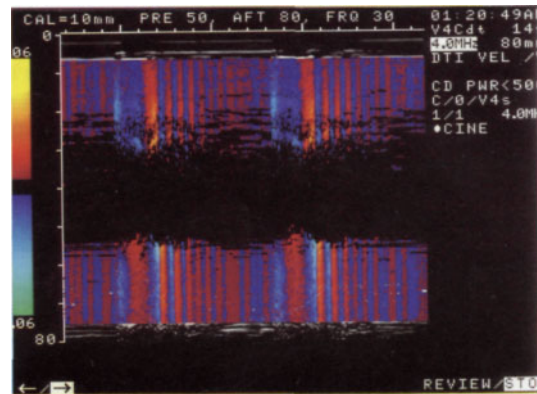


Figure 4. Tissue velocity imaging M-mode of ovine skeletal muscle ventricle contraction. During the two contractions, the subcutaneous (upper) wall and deep (lower) walls move inwards. Relaxation is denoted by reversal of direction of wall motion and color phase. The skeletal muscle ventricle oscillates after contraction. (X-axis = time; one tick = 0.2 seconds. Y-axis = tissue depth; one tick = 10 millimeters. Red/yellow coloration represents motion towards the transducer, blue/green represents motion away from the transducer. Velocities are in metres/second).

possible with the development of newer myostimulators (e.g. Medtronic 4710 Transform) which allow automatic adjustment of burst duration according to heart rate, and more flexible adjustment of burst frequency and synchronization ratio. The effect of these factors on muscle contraction, relaxation and fatigue have yet to be evaluated clinically; TVI provides a method for such an evaluation. Conditioning of skeletal muscle before surgery, using exercise, anabolic steroids, and electrostimulation have been considered as potential methods of improving muscle quality before surgery [5, 6]. Using an appropriate insonation frequency, it should be possible to evaluate whether TVI derived indices of muscle contraction, under standardized loading or stimulation conditions, reflects histological indices of fibre type before surgery. Finally, it should also be possible to evaluate TVI as a test of skeletal muscle function in non-cardiovascular applications such as detrusor myoplasty and gracilis anoplasty [4, 15].

Conclusion

Tissue velocity imaging is a useful modality for examining dynamic skeletal muscle assist systems. In cardiomyoplasty, it provides unique information about the dynamics of myograft function and its effect on ventricular wall motion. Such capabilities may be useful for individualizing stimulation settings. *In-situ* assessment of skeletal muscle function has been shown to be possible in healthy volunteers, but further evaluation is required before TVI can be applied to assess latissimus dorsi quality before surgery. TVI is also currently under evaluation for assessing the function of skeletal muscle ventricles, and preliminary results suggest that it may be useful for long-term monitoring of these systems.

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