

Non-invasive MRI arterial-venous difference measurement of skeletal muscle oxygen consumption during isometric contractions.

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Introduction:

The dependence of blood transverse relaxation and susceptibility on oxygen saturation is commonly exploited for functional MRI studies of brain and other tissues. Although less commonly done, the same effects can be exploited to measure oxygen saturation of blood within resolved vessels, and together with vascular flow measurements, enables measurement of tissue oxygen consumption by arterial-venous difference. This approach has previously been applied to measure global brain oxygen consumption (1,2), and to monitor the time course of flow and venous saturation in large limb vessels during ischemia-reperfusion (3). The purpose of this study was to extend these methods to the smaller vessels supplying the anterior tibial (AT) muscle of the lower leg, and thereby obtain quantitative measurements of the oxygen cost of skeletal muscle contractions completely non-invasively by MRI.

Methods:

Four young adult subjects (21-25 yrs., 1 female) completed the study after giving informed, written consent. The subjects lay supine in a GE 3T Twin-Speed system (GE Medical, Milwaukee, WI, USA), with the right foot secured to a custom-made device for measuring the force of ankle dorsiflexion. Previous ³¹P-MRS studies using the same device showed that metabolic changes during dorsiflexion contractions were confined to the AT muscle (4). Maximum voluntary force (MVC) of ankle dorsiflexion contractions was measured as the average of the 2 strongest of 3-4 test isometric contractions. The volume of the AT muscle was measured from axial fast spin-echo images (256x192 matrix, 16 cm FOV, 0.5 cm slice, ETL 4, TR/TE=2000/12.4), and the location of the AT vessels was determined from maximum intensity projections across an axial stack of time-of-flight images (GRE, 256x162 matrix, 14 cm FOV, 0.2 mm slice, TR/TE=33/7.3). A single oblique slice was chosen 2-3 cm below the bifurcation of the AT and posterior tibial arteries, with the oblique plane perpendicular to the vessel direction. Mean AT artery flow at this slice was measured by peripheral-gated fast CINE phase contrast (256x128 matrix, 12-14 cm FOV, 0.7 mm slice, TR/TE= 8/4.3, 20 cardiac phases, 80 cm/s VENC), and T₂* relaxation rate of intravenous blood was measured by spoiled multi-echo GRE (256x128 matrix, 14 cm FOV, 0.7 cm slice, TR/TE=215/7.6,13.0,18.5,23.9). Venous percent hemoglobin saturation was calculated from T₂* as reported by Zhao et al (5), and fully-saturated and arterial blood oxygen contents were assumed to be a constant 20 ml O₂/ml blood. Subjects performed 2 min duration isometric contractions at 5%, 10%, and 20% MVC (total of 6 contractions), and flow or T₂* measurements (in pseudo-random order) were made at 30 s intervals before, during, and for 3.5 min of recovery after each contraction.

Results:

Figure 1 shows the average AT artery flow (top panel, ±SE, n=4), average venous fractional hemoglobin saturation (middle), and average calculated oxygen consumption (bottom). As expected, the flow increase during 10% MVC contractions was twice that during 5% MVC contractions, and in both cases flow declined immediately during recovery. In contrast, the increase in flow during 20% MVC contractions was only 56% greater than during 10% contractions, and elevated flow persisted during recovery, suggesting that increased tissue interstitial pressure during 20% MVC contractions impeded flow. Mixed venous oxygen saturation tended to rise during the contractions and fall during recovery, but this pattern varied between different subjects. Nonetheless, as expected, the total increase in oxygen consumption above rest, integrated across both the contraction and recovery periods, was proportional to the force of contraction (Figure 2).

Discussion:

To our knowledge this is the first quantitative measurement of the oxygen cost of human skeletal muscle contractions made by an MRI arterial-venous difference method. The net measured oxygen cost of the 20% MVC contraction was 19.46 ml O₂/ min/100 ml muscle. Assuming a contractile P/O₂ ratio of 6, this translates to a mean contractile ATPase rate of 0.87 umole ATP/s/ml, about half of that measured during very short duration maximal contractions by ³¹P-MRS (4).

References:

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