Closer to the edge? Contractions, pressures, waterfalls and blood flow to contracting skeletal muscle

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THE MECHANICAL EFFECTS OF muscle contraction on blood flow to the muscle tissue are interesting, complex, and, we believe, important. It is clear that forceful muscle contractions can stop arterial inflow and propel blood rapidly from the veins. Although there is no controversy about vigorous contractions stopping arterial inflow, controversy continues about the relative importance of the “muscle pump effect” facilitating muscle perfusion during rhythmic contractile activity. Many physiologists believe this controversy is not cutting edge or that the muscle pump makes a minor contribution to venous return but no contribution to muscle blood flow. However, recent evidence demonstrating high muscle blood flow during exercise in conscious animals (including humans) and discussions about exercise hyperemia at the onset of exercise have brought renewed interest to this controversy. Two manuscripts contained in this issue of the Journal of Applied Physiology focus attention on these issues [Hamann et al. (5) and Dobson and Gladden (1)].

The muscle pump hypothesis emerged from observations on the interaction of gravity and walking on venous pressures in human limbs (10). Folkow and colleagues (3) demonstrated that blood flow to contracting human calf muscles was greater when the limbs were in the dependent position (upright posture) than when the limbs were at heart level (supine). Since these fundamental observations, there have been a number of studies examining the relative importance of the muscle pump in providing muscle blood flow (6, 7), and the main conclusion seems to be “it depends.” Rhythmic muscle contraction can interfere with blood flow under a number of conditions (1, 5, 7), and rhythmic contraction can be responsible for 30–60% of the driving force for skeletal muscle blood flow (11, 12).

The study of Hamann et al. (5) employed an elegantly instrumented animal model of treadmill exercise to determine whether the muscle pump increases blood flow in skeletal muscle vasculature that is already vasodilated. Hamann et al. infused adenosine into the femoral artery at a rate that increased blood flow more than the blood flow measured when the dog walked at 3 miles/h on the treadmill. At the initiation of treadmill (3 miles/h), exercise blood flow decreased in the leg vasodilated with adenosine, whereas a normal hyperemic response was observed in the contralateral leg. Thus, not only was no muscle pump effect observed, blood flow decreased with imposition of locomotory exercise. As indicated below, this result may be related to the lack of a significant hydrostatic column in these subjects.

The study of Dobson and Gladden (1) also examined the effects of rhythmic muscle contractions on peak skeletal muscle blood flow in dog skeletal muscle. The gastrocnemius muscle preparation was perfused spontaneously, and the muscle was stimulated to contract with tetanic contractions (200-ms duration, 50 Hz), at one per second. This is a powerful preparation that can be used to determine the effects of contraction on blood flow with tight control of the experimental conditions. The results indicate that muscle contraction, during maximal vasodilation, decreased blood flow, and the authors correctly conclude that their experiment provides no evidence of a muscle pump effect. These results may also be influenced by lack of a hydrostatic column in the preparations. In addition, there is concern that the venous flow probe-cannulation system used may have modified the compliance characteristics of the venous system sufficiently to interfere with the muscle pump effect inasmuch as muscle contraction increased venous pressures from 4–5 to 8–10 mmHg (8).

Have these two new papers finally “solved” all outstanding issues related to the muscle pump and the mechanical interactions of contractions and perfusion in active muscle? The simple answer is no. The observations of Hamann et al. (5) and Dobson and Gladden (1) demonstrate that during drug-induced vasodilation no muscle pumping effect is apparent in isolated, con-
tracting canine calf muscles or in the hindlimb of a dog walking on the treadmill because muscle contraction decreased blood flow in both experiments. Interpretation of these observations requires that we consider factors believed to influence the efficacy of the pumping action of muscle contraction, including the following: 1) adequacy of venous valves (6, 9); 2) gravity and/or effects of venous filling pressures; 3) force, frequency, and duration of rhythmic contractions; 4) recruitment patterns for the muscle contraction (this may be of greatest importance in large muscle groups); 5) fiber type composition of the muscle (and the related vascular volume of the tissue); and 6) location of the muscle tissue in the muscle group (i.e., deep vs. superficial) (6, 7). When the observations of Hamann et al. (5) and Dobson and Gladden (1) are viewed in this context, it appears that the effects of gravity and/or effects of venous filling pressures are key. To establish whether there is a muscle pump effect on muscle blood flow during exercise, future work must determine the importance of the increases in arterial and venous pressures produced by gravity and the hydrostatic column effect (and the effects of venous pressure on venous filling) to the ability of the muscle pump to facilitate blood flow. It is possible that the muscle pump is of greatest importance in perfusion of active skeletal muscle in dependent limbs of humans.

Another important issue is whether results from in situ preparations in experimental animals can be extrapolated to “real” locomotion. In general, in situ preparations indicate that the muscle pump has little or no effect on muscle blood flow, whereas results from studies of locomotion with normal muscle perfusion and normal muscle fiber recruitment patterns indicate that the muscle pump is important in skeletal muscle perfusion during exercise (8). The fact that Hamann et al. (5) saw no evidence of a muscle pump effect is important because the dogs used in their study were involved in normal treadmill exercise with no instrumentation of the veins. An example of the continuing divergence of results in recent literature is provided by the recent paper by Shiotani et al. (11) demonstrating that femoral artery blood flow is nearly twofold higher during cycle exercise in the upright posture than during the same intensity of exercise in the supine position. Thus reports from studies with conscious humans continue to indicate that the muscle pump effect is important in providing skeletal muscle blood flow during exercise. Perhaps, the muscle pump mechanism is of greater importance in humans (and other large mammals with significant hydrostatic columns) than in quadrupeds that have most of their active muscle mass at heart level. Indeed, the key role played by gravity and venous pressure in the muscle pump effect in humans (3, 11) and in isolated feline skeletal muscle (2) suggests that the muscle pump mechanism would not be important in a mammal with little or no hydrostatic column.

Finally, both papers (Hamann et al. (5) and Dobson and Gladden (1)) discuss the idea that a “vascular waterfall effect,” produced by muscle contraction, may negate the muscle pump effect of contraction. The flow of water over a waterfall is independent of how far the water falls to the base of the falls (downstream pressure) or of resistance to flow in the lower river. In the vascular system, if extravascular pressure exceeds intravascular pressure and the blood vessel in question is collapsible, the vessel collapses. Under these conditions, blood flow is independent of downstream vascular resistance and venous pressure (downstream of the closed vessel), i.e., “the vascular waterfall effect.” Dobson and Gladden (1) state that “the presence of a vascular waterfall, or Starling resistance, at the arterioles would prevent any increase in flow through a muscle due solely to a decrease in pressure on the venous side.” During forceful contraction of skeletal muscle, this statement is true (i.e., while the muscle is contracted, venous pressure will have no effect on muscle blood flow). However, a “vascular waterfall” during muscle contraction does not negate a muscle pump effect. Rather, the concept of the muscle pump effect requires a series of “vascular waterfalls” within the vascular bed of skeletal muscle, at different times during rhythmic contractions (stride cycle). It appears that neither capillaries nor arterioles are compressed during muscle contraction; the compression appears to occur in the venous circulation and in larger arteries (4). Thus, during muscle contraction, there is a “vascular waterfall” in that venous pressures have no effect on arterial inflow (indeed, during forceful muscle contraction arterial inflow stops). In contrast, during muscle contraction, the smallest veins in deep muscles have pressures much higher than the femoral vein so blood flows out at high velocities. At the onset of relaxation, blood flow is also not proportional to the pressure difference between femoral artery and femoral vein; i.e., there is also a “vascular waterfall.” During relaxation, blood flows from the arteries into the small veins where pressure is very low (presumably less than femoral vein pressure). Pressure in the small veins is proposed to be very low at this time in the cycle because relaxation of the muscle opens the small veins within the muscle. This hypothesis has not been tested, but examination of the tethering of microvessels within muscle and the tissue architecture of skeletal muscle is consistent with this proposal and suggests that these veins function differently from the veins in more compliant tissue like the lung (6, 7). Thus, during rhythmic contractions, a vascular waterfall effect can be seen. The question is when the entire contraction-relaxation cycle is examined what is the net effect of rhythmic contractions on average blood flow?

The papers of Hamann et al. (5) and Dobson and Gladden (1) provide important results pointing to our largest voids in understanding these phenomena. Further understanding requires that we establish the relationship between the muscle pumping ability of a preparation and venous pressures (is there a minimal venous pressure necessary for the muscle pump to be activated?), duration of tetanic contractions, and frequency of contractions. In our view, the most solid evidence from the current literature for a muscle pump effect comes from experiments in human subjects and...
It is possible that the muscle pump evolved, or was created, to take advantage of the hydrostatic column effect for efficient perfusion of skeletal muscle in dependent limbs. If so, the muscle pump may only function in the presence of gravity and hydrostatic columns. It seems that experiments could be done to address these questions in a preparation like that described by Dobson and Gladden (1) to confirm or refute the results of Folkow et al. (2). It is also important to determine whether venous pressure and the effects of gravity on arterial and venous pressure influence muscle pump stroke volume and muscle pump effectiveness during normal exercise in a quadruped. The model used by Hamann et al. (5) seems ideal for these experiments. Perhaps dogs could be trained to perform locomotory exercise with their hindlimbs in a dependent position, i.e., located below heart level. In addition, it is important to determine the effects of vasodilation and venodilation on the muscle pump.

In conclusion, the question of whether rhythmic muscle contraction combined with normally functioning venous valves enhances or hinders skeletal muscle blood flow has some similarities to the importance of locks in the Panama Canal for the transport of ships. In the presence of differences in water levels between the two oceans, the locks of the Panama Canal facilitate ships going from one ocean to the other; i.e., the locks allow the ships to go up a pressure gradient. However, if there were no difference in water levels between the two oceans, transport would be faster through the canal with no locks. In like manner, the muscle pump may only facilitate muscle blood flow under conditions in which a significant hydrostatic column exists in dependent regions, as in upright exercise in humans.

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