Increases in intramuscular pressure raise arterial blood pressure during dynamic exercise


Department of Integrative Physiology and the Cardiovascular Research Institute, University of North Texas Health Science Center, Fort Worth, Texas 76107-2609

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Gallagher, K. M., P. J. Fadel, S. A. Smith, K. H. Norton, R. G. Querry, A. Olivencia-Yurvati, and P. B. Raven. Increases in intramuscular pressure raise arterial blood pressure during dynamic exercise. J Appl Physiol 91: 2351–2358, 2001.—This investigation was designed to determine the role of intramuscular pressure-sensitive mechanoreceptors and chemically sensitive metaboreceptors in affecting the blood pressure response to dynamic exercise in humans. Sixteen subjects performed incremental (20 W/min) cycle exercise to fatigue under four conditions: control, exercise with thigh cuff occlusion of 90 Torr (Cuff occlusion), exercise with lower body positive pressure (LBPP) of 45 Torr, and a combination of thigh cuff occlusion and LBPP (combination). Indexes of central command (heart rate, oxygen uptake, ratings of perceived exertion, and electromyographic activity), cardiac output, stroke volume, and total peripheral resistance were not significantly different between the four conditions. Mechanical stimulation during LBPP and combination conditions resulted in significant elevations in intramuscular pressure and mean arterial pressure from control at rest and throughout the incremental exercise protocol (P < 0.05). Conversely, there existed no significant changes in mean arterial pressure when the metaboreflex was stimulated by cuff occlusion. These findings suggest that under normal conditions the mechanoreflex is tonically active and is the primary mediator of exercise pressor reflex-induced alterations in arterial blood pressure during submaximal dynamic exercise in humans.

afferent neural signals from exercising skeletal muscle (i.e., exercise pressor reflex) in conjunction with contributions from higher brain centers (i.e., central command) are capable of increasing sympathetic nerve activity (30) and blood pressure (1, 8, 12, 13). The afferent nerve signals arise from mechanically (mechanoreceptors) and chemically sensitive (metaboreceptors) nerve endings located strategically within the muscle (11). Previously, Williamson et al. (31) reported that the application of 45 Torr lower body positive pressure (LBPP) to the lower limbs of the resting human significantly increased mean arterial pressure (MAP). Subsequently, the use of epidural anesthesia to inhibit afferent feedback from resting skeletal muscle eliminated the reflex increase in MAP elicited by lower limb compression (32). The authors suggested that a pressure-sensitive (i.e., mechanoreceptor-mediated) reflex within skeletal muscle was the mechanism by which MAP was increased. Other investigations have confirmed the presence of mechanically sensitive receptors in animals that reflexively increase MAP (10, 17, 27).

Williamson et al. (31) further demonstrated that 15, 30, and 45 Torr LBPP induced incremental increases in MAP at rest that were maintained throughout a progressive exercise test to maximum. Because this response was elicited at rest and during the early stages of work, the investigators suggested that the mechanoreceptor reflex was tonically active and may have been the primary modulator of blood pressure during the exercise trial (31). They speculated that a critical reduction in muscle blood flow was required before the muscle metaboreflex could be activated. In agreement, utilizing terminal aortic occlusion to progressively reduce blood flow to the hindlimbs of exercising dogs, Sheriff et al. (24) indicated that accumulation of metabolic by-products could induce a powerful muscle metaboreflex at moderate workloads. Using indirect methods in humans, Rowell et al. (22) estimated that progressive increases in LBPP during exercise (25, 35, 45, and 50–60 Torr) reduced muscle blood flow by 5.3–19.9%. This investigation reported a stepwise increase in blood pressure to increases in LBPP at rest that was maintained throughout exercise. The findings suggested that a LBPP-induced decrease in leg blood flow (via reductions in venous and leg conductance) resulted in a mismatch between skeletal muscle blood flow and metabolism activating the metaboreceptor reflex. The authors argued that the muscle metaboreflex was the mechanism by which MAP was increased. Thus separate experiments (22, 31) using the same LBPP technique have demonstrated that afferent neural signals arising from active skeletal muscle contribute to the increase in blood pressure during exercise. However, the studies disagree as to whether the LBPP-
induced increases in MAP are due primarily to metabo-
receptor or mechanoreceptor activation.

In the present investigation, we attempted to isolate
the metaboreceptor response via reductions in venous
outflow by utilizing two-legged cuff inflation to 90 Torr
and compared the response to control, 45 Torr LBPP,
and a combination of LBPP and cuff inflation during
progressive work rate dynamic cycle exercise to maxi-

mum. The investigation was designed to determine the
role of intramuscular pressure (IMP)-sensitive mecha-

noreceptors and chemically sensitive metaborecep-
tors in the control of blood pressure during dynamic

exercise.

METHODS

Subjects

Six men and four women, age 27 ± 1 yr (mean ± SE),
volunteered to participate in this investigation (study 1). In a
subgroup of six additional subjects (four men, two women;
mean age 27 ± 2 yr), a second set of experiments (study 2)
was performed. Before they were tested, subjects were in-
formed of all aspects of the study, and each signed an in-
formed consent approved by the Institutional Review Board
for the Use of Human Subjects at the University of North
Texas Health Science Center at Fort Worth. All subjects were
nonsmokers, were not taking medication, and were asymp-
tomatic for cardiovascular and respiratory disease. The sub-
jects were familiarized with all testing procedures and were
asked to abstain from alcoholic beverages and exercise for
24 h and from caffeinated beverages for 12 h before any
scheduled testing session. Subject characteristics are sum-
marized in Table 1.

Exercise Testing

Each subject performed a preliminary incremental work
rate (100 kg-m/min) exercise test on a cycle ergometer (Quin-
ton 845) to volitional fatigue for the determination of peak
oxygen uptake (VO₂peak). Because none of the subjects
achieved a plateau of oxygen uptake (VO₂) with increasing
work rates, the maximum VO₂ achieved was presented as
VO₂peak. On separate days after the initial exercise test, the
subjects performed four additional incremental exercise tests
administered in random order. The four exercise tests were
performed in a 70° back-supported semirecumbent position
in increments of 20 W. All four tests were performed under
distinctly different conditions: 1) exercise with no inter-
vention (control), 2) bilateral thigh cuff occlusion of 90 Torr (cuff
occlusion), 3) LBPP of 45 Torr (LBPP), and 4) a combination
of thigh cuff occlusion of 90 Torr and 45-Torr LBPP (combi-
nation). The administration of thigh cuff occlusion, LBPP, or
the combination of both was applied to the subject at rest,
and exercise was initiated after a collection period of baseline
measurements for 5 min.

Two exercise tests were performed on a single day sepa-
rated by a minimum of 3 h with each testing day separated by
a minimum of 4 wk. Because the data obtained from the
initial upright incremental exercise test and the randomized
exercise test without intervention in the semirecumbent
position were similar, the latter test was referred to as the
control test. A custom-designed LBPP chamber (Fig. 1)
equipped with a computerized, electromagnetically braked
cycle ergometer (Intellifit, Houston, TX) allowed subjects to
exercise in a semirecumbent position (back angle at 70°).
This back angle was chosen to simulate upright exercise as
much as possible to allow for maximal effort and subject
comfort. The subject’s lower body was sealed with a polyprop-
ylene skirt fitted snugly around the iliac crest. Chamber
pressure was continuously monitored from a digital trans-
ducer (Universal Pressure Meter, Bio-Tek). Positive pressure
driven by vacuum motor pumps was applied to the subjects
lower body inside the chamber. Shoulder straps attached to
the seat back were utilized to maintain the subject’s position
when LBPP was applied. During cuff occlusion and combina-
tion conditions, venous occlusion pressures were applied with
large adult blood pressure cuffs secured around the subject’s
upper thighs. The cycle ergometer was adjusted for each
subject so that a knee angle at maximal leg extension was
consistent for all tests. Subjects were instructed to keep their
arms relaxed on trays set at heart level.

The cycle ergometer was interfaced with a personal com-
puter that was preprogrammed to begin at a load of 13 W for
an initial 3-min warm-up stage, increase to 20 W for the
second stage, and increase by 20 W each minute until the
subject achieved volitional fatigue. Subjects were requested
to maintain a pedal cadence of 60 rpm for the duration of the
test verifiable by visual feedback from a computer monitor.

Table 1. Subject information

<table>
<thead>
<tr>
<th></th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>VO₂peak, ml·min⁻¹·kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study 1</td>
<td>27 ± 1</td>
<td>173.7 ± 3.1</td>
<td>73.5 ± 4.0</td>
<td>40.3 ± 1.7</td>
</tr>
<tr>
<td>(n = 10)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Study 2</td>
<td>27 ± 2</td>
<td>173.7 ± 3.6</td>
<td>73.5 ± 4.8</td>
<td>36.0 ± 1.9</td>
</tr>
<tr>
<td>(n = 6)</td>
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Values are means ± SE. VO₂peak, peak oxygen uptake; n, subject number.

Fig. 1. Experimental setup included a computer-controlled cycle
ergometer housed inside a lower body positive pressure (LBPP)
chamber. LBPP was manually controlled with variable autotrans-
dausers to measure arterial (ABP), central venous (CVP), and
intramuscular (IMP) pressure, respectively. Breath-by-breath oxy-
gen uptake (VO₂) was measured with a turbine flowmeter and mass

transducers to measure arterial (ABP), central venous (CVP), and
intramuscular (IMP) pressures, respectively. Breath-by-breath oxy-
gen uptake (VO₂) was measured with a turbine flowmeter and mass

spectrometer. Electromyographic (EMG) measurements of quadri-
ceps activity were obtained from surface EMG electrodes. Not pic-
tured is the Finapres that was used in 6 subjects, the cardiac output
(Q̇e) rebreathe bag, the retrograde venous catheter, or the shoulder
harness used to maintain subject placement when LBPP was ap-
plied. ECG, electrocardiogram.
Measurements

Study 1. During each exercise test, heart rate (HR) was monitored by a standard lead II electrocardiogram. Arterial blood pressure (ABP) was monitored in six subjects by a Teflon catheter (Angiocath 20GA) inserted in the right radial artery. In four subjects, ABP was measured by a finger cuff using an optomechanical photoplethysmographic method (Finapres, Ohmeda). Previously, we demonstrated validity correlations (0.93–0.99) with no significant difference in the intercept value from zero, between systolic (SBP), mean (MAP), and diastolic (DBP) blood pressure between radial arterial lines and the indirect Finapres during progressive exercise to fatigue (20, 25). Central venous pressure (CVP) was monitored by a double-lumen catheter (Cook Critical Care) positioned via each subject’s median antecubital vein into the superior vena cava at the level between the third and fourth intercostal space. Placement was confirmed under fluoroscopic observation (BV22, Philips, Eindhoven, The Netherlands). Both CVP and ABP catheters were connected to a sterile disposable pressure transducer (Cobe, Lake Wood, CO) interfaced with a pressure monitor (model Hewlett-Packard 78205D/7803B, or Tektronix 414). The zero reference pressure was set at heart level for both CVP and ABP (direct and indirect) measures.

Changes in IMP (ΔIMP) were monitored by insertion of an intramuscular catheter into the rectus femoris muscle between the iliac crest and the medial condyle of the tibia ~2∕3 distal to the iliac crest. ΔIMP was monitored with a microtip pressure transducer (model PC-330A, Millar, Houston, TX). During each experiment, HR, CVP, ΔIMP, and ABP (i.e., MAP, SBP, and DBP) were acquired by using a beat-to-beat customized software data-acquisition system interfaced with a personal computer (Gateway 2000). In addition, ratings of perceived exertion (RPE) were obtained for both whole body (RPEbody) and exercising legs (RPElegs) during warm-up, at 20 W, and at each additional 40-W increment by using a Borg scale (3). Electrodes were placed on the vastus medialis muscle and the vastus lateralis muscle for the indirect monitoring of electromyographic (EMG) activity. Thirty-second averages of the integrated signal during each work rate, including rest, were transmitted to a monitoring system (Mespec 4001 EMG system, Kuopio, Finland).

The subjects respired through a mouthpiece attached to a low-resistance turbine volume transducer (Sensor Medics, VMM series) for measurement of breath volumes while respiratory gases were continuously sampled from the mouthpiece for analysis of fractional concentrations of oxygen, carbon dioxide, and nitrogen by mass spectrometry (Perkin-Elmer MGA1100B). The mass spectrometer was calibrated before each test by using known high-precision standard gases. Device input signals underwent analog-to-digital conversion and computer analysis (Dell Optiplex GXi) for online, breath-by-breath determinations. A customized software package was employed to correct for equipment delay and response times. Standardized calculations of metabolic data were corrected for ambient conditions and measurements were averaged for each workload. In addition, cardiac output (Qc) was determined by using the acetylene rebreathe technique (29). Qc was determined at rest, warm-up, 40 W, and each additional 60 W throughout the protocol until maximum. Stroke volume was calculated as Qc/HR, and total peripheral resistance (TPR) was calculated as (MAP – CVP)/Qc.

Study 2. These experiments consisted of repeating the protocol used in study 1 with six different subjects using the previously described measurements of HR, ABP (direct arterial catheter in 4 subjects and indirect in 2 subjects), and VO2. In this protocol, venous blood samples were obtained via a 20-gauge angiocatheter inserted in the median antecubital vein of the right arm. In addition, an 8-in. femoral venous catheter (Arrow 16 gauge) was inserted into the femoral vein and passed slowly retrograde from the area below the inguinal canal to a measured distance that ensured that the tip of the catheter was below the venous occlusion cuff. This allowed for blood sampling below the occlusion cuff representative of perfusate from the skeletal muscle, skin, and bone of the active limb. Triplicate samples obtained every 40 W of exercise from both venous catheters were analyzed for blood lactate concentrations (average values reported) by using an enzymatic technique (Radiometer, Copenhagen, Denmark).

Study 2 did not contain measurements of CVP, ΔIMP, Qc, or EMG.

Statistical Analysis

A two-way ANOVA with repeated measures across the main effects of the four different conditions and work rate was employed to determine significant differences during incremental work rate exercise. The absolute work rates were used for the calculation of group means for each condition. Student-Newman-Keuls post hoc pairwise comparisons were used to establish significant group mean differences. Data are presented as means ± SE. The alpha level was set at P < 0.05. All analyses were conducted by using Statistical Analysis Systems (SAS Institute, Cary, NC) and Sigma Stat (Jandell).

RESULTS

During incremental exercise, VO2peak and peak work rate were significantly decreased from control exercise during each experimental exercise condition (cuff occlusion, LBPP, and combination; see Table 2). Tests were typically terminated when the subject could no longer maintain pedal cadence or requested that the session end. Most of the subjects reported that leg fatigue was the primary reason for the cessation of exercise rather than cardiorespiratory limitations. This was reflected by significant elevations at all work rates in RPElegs in each condition from control until 160 W (RPElegs data not shown).

There were no significant alterations in HR, EMG, VO2, and RPEbody across the four exercise conditions at all work rates including rest (Fig. 2). The application of cuff occlusion, LBPP, and combination conditions did not significantly alter Qc (Fig. 3), stroke volume, and

Table 2. Peak oxygen uptake and peak work rates achieved during each exercise condition

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Cuff Occlusion (90 Torr)</th>
<th>LBPP (45 Torr)</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO2peak, l/min</td>
<td>2.99 ± 0.32</td>
<td>2.47 ± 0.67*</td>
<td>2.38 ± 0.63*</td>
<td>2.24 ± 0.79*</td>
</tr>
<tr>
<td>Peak work rate, W</td>
<td>266 ± 24</td>
<td>212 ± 24*</td>
<td>208 ± 16*</td>
<td>187 ± 22*</td>
</tr>
</tbody>
</table>

Values are means ± SE. LBPP, lower body positive pressure. *Significantly different from control.
TPR from control at rest nor during any work rates. In addition, the data presented in Fig. 3 illustrate that CVP was significantly elevated from control and cuff occlusion with the application of LBPP and during combination conditions with exercise. CVP during the LBPP condition became significantly increased from the combination condition after 60 W. This occurred because CVP during the combination condition began to decrease after 20 W and approached the CVP measured during cuff occlusion and control conditions.

MAP and DBP were significantly elevated from control during both LBPP and combination conditions (Fig. 4). These increases were initiated at rest and were preserved throughout the incremental exercise protocol. Likewise, SBP was significantly elevated from control at 40, 60, 80, and 100 W during both LBPP and combination conditions (Fig. 4). Cuff occlusion did not produce significant elevations in MAP, SBP, or DBP from control. ∆IMP was significantly elevated from control and cuff occlusion trials at rest and throughout exercise during both LBPP and combination conditions, suggesting a mechanical stimulus was activated (Fig. 4). There was no difference in ∆IMP between control and the cuff occlusion conditions. Figure 5 contains one individual’s representative MAP responses to the four exercise conditions from the initiation of exercise to maximum. The slope of representative beat-by-beat measurements of MAP exhibited linear increases with no alterations until maximum for all exercise conditions.

In study 2, HR, SBP, DBP, MAP, and VO₂ demonstrated similar responses as in study 1 (data not presented). Lactate measured from the active skeletal
muscle was significantly elevated from control at 120, 160, and 200 W during cuff occlusion, LBPP, and combination conditions (Fig. 6). However, lactate was not significantly different between cuff occlusion, LBPP, and combination trials. Peripherally measured lactate (estimating total body lactate) was not significantly altered from control by any of the conditions (Fig. 6).

**DISCUSSION**

In the present investigation, we confirmed an augmented blood pressure response with the application of LBPP of 45 Torr. The major new finding from this study was that a significant augmentation in the blood pressure response did not occur when metabolites were trapped in active muscle with the application of thigh cuff occlusion alone. These responses suggest that pressure-sensitive mechanoreceptors are the primary mediators of the exercise pressor reflex-induced increase in blood pressure during dynamic exercise.

The cardiovascular responses to exercise have been demonstrated to be mediated in part by signals from central command (5–7, 9, 23). Consistent with previous studies (31), we demonstrated reductions in peak work rate and V\textsubscript{O2} peak from control during conditions of cuff occlusion, LBPP, and combination (Table 2). This decrease in work performance could be attributed to fatigue leading to recruitment of additional muscle fibers through the activation of central command. Historically, certain variables (RPE\textsubscript{body}, HR, EMG, V\textsubscript{O2}) have been used as indexes of central command (6, 8, 12, 14, 23). In this investigation, we did not demonstrate any significant differences in HR, EMG, V\textsubscript{O2}, or RPE\textsubscript{body} at the same absolute work rates (Figs. 2 and 3) between control and the cuff occlusion, LBPP, or combination conditions. This would suggest that the influence of central command was similar during each exercise condition at the same absolute work rate. In addition, subjects did not report any pain during the exercise bouts, suggesting that there was no enhancement of nocioreceptor activation. Thus we reasoned that any differences in the blood pressure responses among conditions were primarily due to the reflex stimulus from the active skeletal muscle with minimal influence from central command.

Alam and Smirk (1) and Rowell et al. (21) have reported that the use of total circulatory occlusion in humans immediately before the termination of maximal exercise traps metabolites in active muscle, resulting in a sustained increase in MAP. They have attributed this pressor response to the activation of muscle metaboreceptors. Using a similar method in animals (i.e., terminal aortic occlusion), Wyss and colleagues (33) induced graded decreases in hindlimb blood flow in dogs during dynamic exercise. At moderate-to-high workloads, they demonstrated significant increases in aortic pressure in response to decreases in muscle blood flow (a potent metaboreceptor stimulus). However, at low workloads, cardiovascular responses to exercise were affected only by substantial reductions in hindlimb perfusion (33). Therefore, it was suggested that signals other than feedback from metabolically sensitive muscle receptors must be involved in the regulation of the cardiovascular system during low-intensity exercise (33).

Total circulatory occlusion, as described by Alam and Smirk (1) and Rowell et al. (23), hinders a subject's...
ability to exercise. To address this limitation, we used thigh cuff occlusion of only 90 Torr. It has been reported that blood is translocated toward the central circulation during forceful rhythmic contractions at a driving force of 90 mmHg (28). Therefore, the occlusion technique utilized allowed the trapping of metabolites within the working skeletal muscle without the confounding mechanical effects of externally applied pressure (i.e., LBPP). LBPP is also known to trap metabolites at moderate workloads (4, 22). Both Rowell et al. (22) and Eiken and Bjurstedt (4) attributed LBPP-induced increases in blood pressure to metaboreflex activation. Oelberg et al. (16), using cuff occlusion of 45 Torr, noted a decrease in pH of 0.2, which is similar to the decrease in pH reported when using LBPP of 45 Torr during moderate exercise (22). However, LBPP also increases IMP (Fig. 4) and acts as a mechanical stimulus (26). Given that LBPP and cuff occlusion have been shown to decrease pH to a similar degree but only LBPP increases IMP, we reasoned that any difference in the pressor response to exercise was due to the mechanical stimulus induced by LBPP.

To assess the efficacy of the trapping mechanisms induced by cuff occlusion and/or LBPP application, a retrograde venous catheter was threaded into the femoral vein below the level of the thigh cuff for the measurement of lactate. Lactate measured from the active limb was significantly elevated from control exercise during both cuff and LBPP application. Furthermore, during cuff occlusion, LBPP, and combination conditions, lactate levels were not different, suggesting that each method trapped metabolites equivalently. This finding does not suggest that lactate is the primary agent for metaboreceptor stimulation or that a mismatch in blood supply and demand is necessary to activate the metaboreflex. On the contrary, the substances mediating metaboreflex responses to exercise remain incompletely understood. Potential candidates include, but are not limited to, arachidonic acid.

**Fig. 5.** Representative MAP tracings from 1 subject. The record begins at the initiation of exercise and continues to maximum during control (no intervention; A) and after the application of bilateral thigh cuffs (cuff occlusion; B), LBPP (C), and combination (D). Beat-by-beat measurements of MAP exhibited linear increases with no alterations through maximal exercise for all conditions.

**Fig. 6.** Femoral (active limb) and peripheral lactate responses to incremental work rate exercise during control and with cuffs (90 Torr), LBPP (45 Torr), and combination conditions. Means ± SE are presented at rest and during exercise. Lactate measured from the active limb was significantly elevated from control at 120, 160, and 200 W during cuffs, LBPP, and combination conditions. However, lactate was not significantly different between cuffs, LBPP, and combination conditions. Peripherally measured lactate (estimating total body lactate) was not significantly altered from control by application of any experimental condition. *Cuffs, LBPP, and combination conditions significantly different from control, $P < 0.05.$
acid, hydrogen ion, and potassium as well as lactate. The lactate measurements in this investigation only provide evidence that thigh cuff occlusion of 90 Torr and/or LBPP of 45 Torr significantly hindered venous outflow as reported previously (15). Therefore, the removal of all by-products of muscle metabolism within the exercising limb was presumably reduced.

Using 90 Torr cuff occlusion, we were unable to induce significant increases in blood pressure from control conditions. This supports the contention that the metaboreflex is not tonically active in the regulation of blood pressure (31). Williamson et al. (31) reported that, during dynamic exercise, additional increases in blood pressure occur at the later stages of exercise above those induced by the application of LBPP. They concluded that the additional break in blood pressure occurred when a sufficient amount of metabolites was produced and trapped in the muscle activating the muscle metaboreflex. We analyzed beat-to-beat blood pressure responses to maximum in each individual to determine whether additional increases in blood pressure, above those induced by LBPP application, were manifest. However, we were unable to identify any further augmentation in the blood pressure response during exercise under any condition up to maximum (Fig. 5). It is possible that, because of the redundant and/or polymorphic nature of metabo- and mechanoreceptors, sufficient stimulation of the mechando reflex throughout exercise may have masked or attenuated metaboreflex activation. In contrast, we recently demonstrated that intramuscle metaboreceptors are a major regulator of ventilation during dynamic exercise to maximum (26). Therefore, it appears that the metaboreflex does play a significant role in cardiorespiratory control during exercise. However, it may only be involved in the regulation of cardiovascular responses when 1) the mechanoreflex is abolished and the metaboreflex continues to be activated (e.g., postexercise occlusion) (14) or 2) there exists some critical decrease in flow such as during ischemia (24, 33).

Therefore, we conclude that the increases in blood pressure observed at rest and during exercise are due to the activation of pressure-sensitive mechanoreceptors. It is possible that this response was mediated by passive displacement of fluid centrally via the mechanical effects of LBPP application. However, given the subject's semirecumbent body position, blood translocation would have been kept to a minimum. More likely, LBPP resulted in an immediate activation of the muscle mechanoreflex via physical distortion of muscle stretch receptors. This is supported by the data presented in Fig. 4, in which LBPP of 45 Torr resulted in an immediate increase in IMP to the same degree at rest as throughout exercise. Furthermore, at rest and during the early exercise work rates, it is unlikely that a sufficient amount of metabolites had accumulated, precluding activation of a metabolically sensitive reflex. Therefore, we propose that, during normal incremental work rate exercise without intervention, input from skeletal muscle mechanically sensitive afferents contributes along with central command and arterial baroreflex resetting to elicit the characteristic progressive rise in MAP (18, 19).

Potential limitations in the design of this study are recognized. Foremost, we were unable to quantify the effect of cuff and LBPP application on leg blood flow during exercise. Common methods for obtaining this measurement (e.g., plethysmography, pulsed-Doppler) are hindered by the movement of the lower limbs during exercise. Additionally, the magnitude of cuff occlusion and LBPP applied was static throughout the exercise protocol. Therefore, it was likely that the efficacy of the mechanisms employed to impede venous outflow and reduce leg blood flow was diminished as SBP and DBP increased with exercise. As such, it is possible that metaboreflex activation differed across workloads with both cuff and/or LBPP application. However, inferential evidence exists in the femoral venous lactate measurements to argue that the metaboreceptor stimulus was consistent between cuff, LBPP, and combination conditions. Furthermore, these values were significantly greater during execution of these experimental paradigms than those determined for control conditions. Likewise, we were unable to accurately quantify the extent to which the mechanoreceptor reflex was activated during the exercise protocols again relying on inferential evidence from IMP recordings. Unfortunately, it is impossible in humans to directly assess neural activity derived from somatosensory afferents within skeletal muscle. Interpretation of the data obtained in this study must involve the careful consideration of the limitations inherent to human investigation.

In contrast to our data, others have previously demonstrated increases from control values in VO2 (4) as well as Qc and HR (4, 22) with the application of LBPP. However, these data were collected on subjects in the supine position rather than the semirecumbent position. This may have allowed the activation of different muscle groups (utilizing additional oxygen) and maximized the fluid translocation that occurs with LBPP (possibly inducing a Bainbridge-type reflex). Such methodological differences could account for the disparity in results reported (2).

In summary, blood pressure was not significantly increased when metabolites were trapped in the active skeletal muscle by cuff occlusion. However, significant increases in blood pressure at rest and throughout exercise occurred during LBPP and combination conditions. Cuff occlusion and LBPP appeared to trap metabolites similarly, suggesting that the differences in the blood pressure response between the two conditions was primarily due to LBPP-mediated mechanoreceptor activation. Furthermore, these changes in blood pressure did not appear to be influenced by central command because there was no alteration in HR, EMG, VO2, and RPEbody between exercise conditions at the same absolute work rates. These data suggest that mechanically sensitive intramuscular receptors are the primary mediators of exercise pressor.
reflex-induced alterations in ABP during dynamic exercise.

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REFERENCES