Factors affecting blood pressure during heavy weight lifting and static contractions

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MacDougall, J. D., R. S. McKelvie, D. E. Moroz, D. G. Sale, N. McCartney, and F. Buick. *Factors affecting blood pressure during heavy weight lifting and static contractions.* J. Appl. Physiol. 73(4): 1590–1597, 1992.—Brachial arterial pressure was directly recorded in 31 healthy male volunteers through protocols examining the effects of the Valsalva maneuver, muscle size and strength, contraction force, contraction type (concentric, isometric, eccentric), changes in joint angle, and muscle fatigue on the blood pressure response to resistance exercise. Weight lifting at the same relative intensity produced similar increases in blood pressure, regardless of individual differences in muscle size or strength. Concentric, isometric, or eccentric exercise at the same relative intensity caused similar increases despite differences in force production. In weight lifting, the greatest increase in blood pressure occurred at the joint angle corresponding to the weakest point in the strength curve and the least at the angle corresponding to the strongest point. Isometric contractions of the same relative intensity at different joint angles produced identical blood pressures despite differences in absolute force production. When subjects attempted to maintain a maximum isometric contraction for 45 s, the blood pressure increase remained the same despite a marked diminution in force. Thus the magnitude of the blood pressure response depends on the degree of effort or central command and not actual force production. A brief Valsalva maneuver, which exaggerates the increase in blood pressure, is unavoidable when desired force production exceeds ~80% maximum voluntary contraction.

pressor response; arterial blood pressure; concentric, isometric, and eccentric contractions; joint angle; Valsalva maneuver

EXTREME INCREASES in arterial blood pressure occur when healthy subjects perform heavy dynamic weight-lifting exercise (10). These increases are the summed effects of a potent pressor response, mechanical compression of blood vessels, and the Valsalva maneuver, and their magnitude is, for the most part, related to the intensity of the exercise. Within each subject, the degree to which blood pressure increases is also affected by the size of the active muscle mass, although this is not a direct relationship (i.e., peak blood pressure is only slightly higher during a double-leg press compared with a single-leg press at the same relative intensity) (10).

During forceful static contractions, the increase in blood pressure is the result of an increase in heart rate and cardiac output and, to a lesser extent, a reflex vasoconstriction in the vessels of nonexercising muscles (13, 14). The mechanisms responsible for this pressor response are believed to include both a central component originating in the supraspinal areas of the brain and a peripheral or reflex neural component originating in the contracting muscles and transmitting along group III and IV muscle afferents to cardiovascular control centers (7, 11, 12). Whether the pressor response that occurs with heavy weight-lifting (dynamic) exercise is similar to that with heavy static exercise is not known. By manipulating such factors as muscle size and strength of subjects, type of contraction, joint angle, and the presence of fatigue, it is possible to uncouple at least partially the normal relationship between the intensity of the effort (central component) and force production (peripheral component) and thus to determine which component has the greatest effect on blood pressure.

It is also known that when a subject performs a Valsalva maneuver, the increase in intrathoracic pressure is transmitted to the arterial tree, causing an abrupt increase in blood pressure (10). During heavy weight lifting, the Valsalva maneuver provides a mechanical advantage by stabilizing the trunk and thus cannot be avoided when subjects perform a maximal contraction or repeated near-maximal contractions to failure. The quantitative contribution that the Valsalva maneuver imparts to the total blood pressure response during weight lifting is not yet known.

This report summarizes a series of studies conducted to further document the factors that affect the blood pressure response to heavy resistance exercise in healthy humans. Factors examined included the contribution of the Valsalva maneuver, the effects of muscle size and strength, the force of contraction, the type of contraction (concentric vs. eccentric vs. isometric), changes in joint angle, and the effects of muscle fatigue on the nature of the blood pressure response to heavy weight-lifting and static exercise.

METHODS

Subjects. A total of 31 healthy male volunteers (21–32 yr) participated in one or more of the various studies. All were fully informed of the purposes of the studies and the associated risks, as required by the Human Ethics Committee of McMaster University. All subjects were physically active and had previous exposure to heavy resistance training, ranging from novices to experienced body-builders and professional football players.

Blood pressure. Blood pressure was directly recorded by catheterization of the brachial artery. For all studies except the muscle fatigue study, pressure was measured by coupling a short fluid-filled column to a Novatrans pressure transducer (model MX807, Medex) as we have previously described (3). For the fatigue study, pressure was directly recorded from an indwelling pressure-tip transducer (Millar, Mikro-Tip). In both systems, the transducer was either positioned at or advanced to the level of the aortic root. Pressure signals were amplified by a Gould Universal amplifier, and mean blood pressure was derived by integration of the signal with use of a custom electronic integrator and divided by time. The linearity of both systems was verified over the range of 0–500 Torr by calibration against a strain-gauge reference transducer. The systems were also calibrated before and after each test with a mercury manometer by injecting pressures between 0 and 200 Torr. The pressure-tip transducer system was cross-referenced against the fluid column system by catheterizing both arms in two subjects. Values and wave formations were found to be identical.

Intrathoracic pressure. Intrathoracic pressure was continuously recorded from a Gaeltec pressure-tip esophageal transducer, introduced nasally and advanced to 30 cm. The transducer was calibrated against a mercury manometer over the range of 0-200 Torr. All data were recorded on a chart recorder and stored on a computer. In addition, signals were directed through an oscilloscope so that subjects had visual feedback on their intrathoracic pressure and thus could maintain a given target pressure.

Exercise equipment. All weight lifting and static contractions were performed on a modified Global leg press apparatus. The footplate was instrumented with a strain-gauge load cell so that leg force (foot pressure) could be continuously recorded. By adjusting seat and/or footplate position, it was possible to achieve a wide range of hip and knee joint angle starting positions. For isometric exercise, the weight stack was fixed so that no movement could occur. To isolate only the concentric or eccentric phase of the lift, the weight stack was fitted with a custom-designed yoke or extension so that assistants could also lift or lower the weight as required. For example, to assess the effects of concentric contractions alone, the concentric phase of the repetition was performed by the subject and the weight was lowered by two assistants. To assess the effects of eccentric efforts alone, the weight was lifted each time by the two assistants but lowered at a controlled velocity by the subject.

Joint angle. In several subjects, knee joint angle was monitored from an elgon positioned at the knee so that joint angle could be determined at any point throughout the performance of the leg press and correlated with the blood pressure response at the same point in time.

Recording and storage of data. All blood pressure, intrathoracic pressure, footplate pressure, and joint angle data were simultaneously recorded on a six-channel Gould chart recorder (Brush 260) and digitized, displayed, and stored on a Zenith IBM-compatible computer. A CODAS software package (Dataq) was used for data analysis.

Effects of muscle size and strength. For this study, 11 volunteers were selected to represent a wide range in thigh muscle size and strength. Body weights ranged from 64 to 123 kg. Cross-sectional area of the quadriceps of each leg was determined by computerized digitizer and manual planimetry of enlarged computed tomography scans (model 2020 HR, Technicare) taken midway between the greater trochanter and lateral epicondyle of the femur.

Arterial blood pressure and intrathoracic pressure were recorded during double-leg presses to failure at 85% maximum voluntary contraction (MVC), which resulted in ~10 repetitions (10 RM) as determined on a previous day.

Effect of contraction type. Blood pressure and intrathoracic pressure were recorded while six subjects performed concentric, eccentric, and isometric exercise at 50, 70, and 87.5% of MVC, respectively. For the concentric and eccentric efforts, the weight stack was lifted or lowered over 3 s to a metronome while two assistants performed the opposite phase of the lift until a total of 10 repetitions were completed. For the isometric effort, force on the footplate was displayed on an oscilloscope and subjects were instructed to maintain the desired force for 30 s. Starting knee joint angle was 90° in all three cases, and the order of exercise was randomized and spread over two separate days to control for the effects of fatigue.

Effect of the Valsalva maneuver. Seated at rest, six subjects performed a series of Valsalva maneuvers at intensities eliciting intrathoracic pressures equal to 20, 40, 60, 80, and 100% of maximum (the highest intrathoracic pressure that could be generated by forceful exhalation against a closed glottis and maintained for 5 s). Intrathoracic pressure was displayed on the oscilloscope, and subjects were instructed to maintain a given target pressure for 30 s or until they could no longer do so. At the higher intensities, subjects found it necessary to take a rapid breath approximately every 6 s to maintain target pressure.

Effect of joint angle. The effect of joint angle was examined by *1*) recording knee joint angle (from an elgon) and blood pressure during dynamic contractions and *2*) recording blood pressure during static or isometric efforts at various fixed joint angles. For the latter method, six subjects performed maximum isometric efforts on the leg press apparatus adjusted to provide a knee joint angle of 75, 90, and 105°. They then maintained an isometric effort at each of these joint angles at an intensity equal to 70% of the respective MVC for 30 s. Force on the footplate was displayed visually so that the target intensity could be achieved and maintained. Three-minute recovery periods were given between trials, and trial order was randomized.

Effect of muscle fatigue. For this study, five subjects performed a maximum isometric effort on the leg press unit and attempted to maintain 100% of their MVC for 45 s. Knee joint angle was 90°, and subjects performed three successive bouts separated by 2-min recovery periods. Verbal encouragement was given throughout each trial. Force on the footplate, blood pressure, and intrathoracic pressure were continuously recorded.

Statistical analyses. Data on the effects of muscle size and strength were analyzed using Pearson's correlation

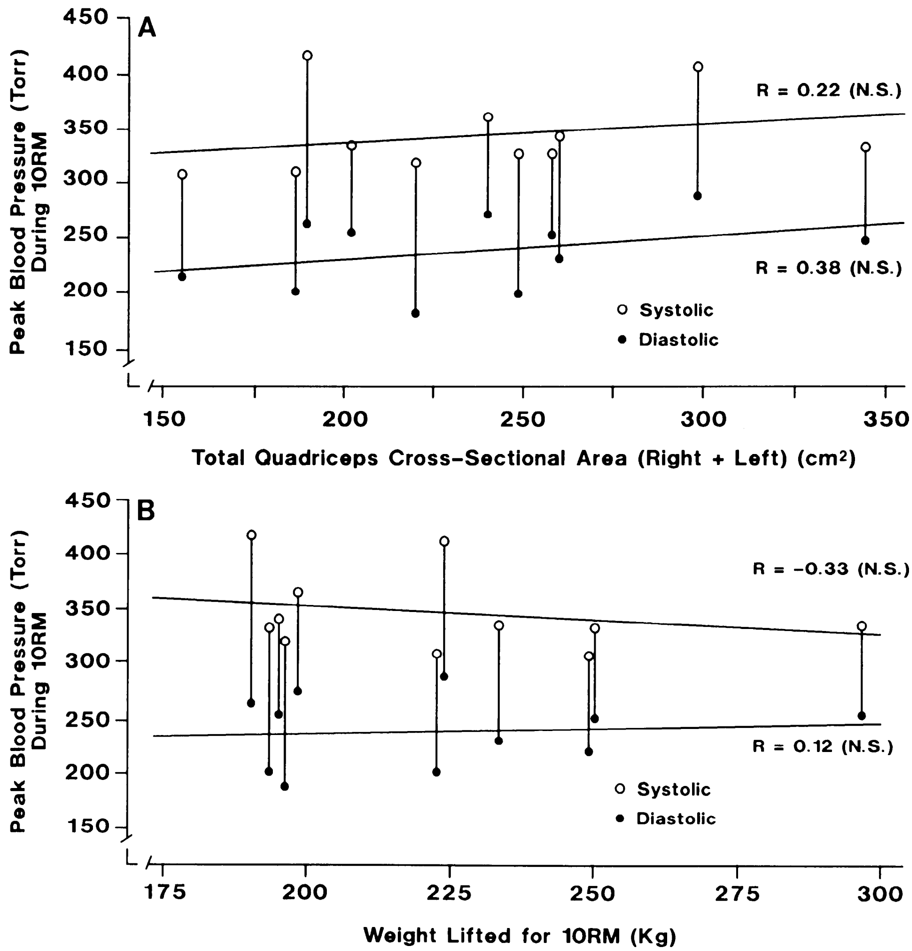

FIG. 1. Peak systolic and diastolic blood pressures graphed against total muscle size (*A*) and absolute weight lifted (*B*) during 10 repetitions maximum (RM). Regression lines for systolic and diastolic blood pressures indicate nonsignificant relationship (n = 11).

coefficient and all other data by a one-factor analysis of variance with repeated measures. A Tukey post hoc test, with the level of significance set at $P < 0.05$, was used to determine significant differences where interactions occurred.

RESULTS

Effect of muscle size and strength. The effects of muscle size and strength on blood pressure during 10–12 RM leg press exercise are illustrated in Fig. 1, *A* and *B*. Despite wide interindividual differences and a very wide range in size and strength, peak systolic and diastolic pressures were independent of muscle size (Fig. 1*A*) or absolute weight lifted (Fig. 1*B*). The mean peak systolic pressure for the 11 subjects was 343 ± 38 (SD) Torr and the mean peak diastolic pressure 235 ± 35 Torr, with pressures in one subject reaching 418/254 Torr.

Effect of contraction type. The effect of the type of contraction on the magnitude of the blood pressure response is summarized in Table 1. Compared with their concentric contraction, subjects were ~26% stronger ($P < 0.05$) when performing a maximum isometric effort and ~56% stronger ($P < 0.01$) when performing a maximum eccentric effort. Thus, although absolute force production varied considerably across the three exercise modes, when contractions were made at the same relative intensity, peak systolic, diastolic, and intrathoracic pressures were the same. Mean blood pressure over 30 s was significantly higher during the 70 and 87.5% MVC isometric contraction because, in this mode, blood pressure did not display fluctuations with each repetition. In contrast, mean blood pressure for the two dynamic modes included the peaks and troughs with each contraction.

Effect of the Valsalva maneuver. The effect of the Valsalva maneuver alone on arterial blood pressure is illustrated in Fig. 2, *A* and *B*. When a subject performs a forceful Valsalva maneuver, there is an immediate increase in systolic and diastolic blood pressures (Fig. 2*A*), directly related for the most part to the magnitude of the increase in intrathoracic pressure (Fig. 2*B*).

Subjects do not find a Valsalva maneuver necessary during heavy resistance exercise unless the required force output exceeds ~80% MVC or repetitions of lighter loads continue to failure. Typical individual traces for two subjects performing submaximal leg press exercise are presented in Fig. 3, *A* and *B*. The resistance in Fig. 3*A* was ~75% MVC, and the subject was able to perform the lifts with only the occasional assistance of the Valsalva maneuver. Arterial blood pressure increased and decreased with each lift in the absence of the Valsalva maneuver, but the increase was exaggerated when the Valsalva was included. In Fig. 3*B*, in which resistance was ~85% MVC, the subject found it necessary to enlist a Valsalva maneuver with each repetition, and the intensity of the Valsalva maneuver increased as the subject approached failure.

Effect of joint angle. The effects of joint angle on the

TABLE 1. *Peak blood pressure, mean blood pressure, and intrathoracic pressure during concentric, isometric, and eccentric contractions*

Type of Contraction	Intensity, %MVC	Force of Contraction, kg	Peak Blood Pressure, Torr		Peak ITP, Torr	Mean Blood Pressure, Torr
			Systolic	Diastolic		
Concentric	50	103±14	200±9	105±8	17±4	108±4
Isometric	50	129±10	200±9	112±7	20±8	113±4
Eccentric	50	157±19	197±8	108±6	23±9	109±4
Concentric	70	147±17	241±13	136±16	49±13	120±4
Isometric	70	176±21	241±12	154±9	41±8	130±3*
Eccentric	70	220±28	221±7	115±10	45±9	116±4
Concentric	87.5	178±20	263±8	142±6	51±8	122±3
Isometric	87.5	225±17	282±14	181±10	75±8	138±5†
Eccentric	87.5	277±34	240±8	144±14	65±8	119±4

Values are means ± SD; $n = 6$. MVC, maximum voluntary contraction; ITP, intrathoracic pressure. Peak pressure is highest pressure recorded during exercise and mean pressure in integrated pressure signals over duration of exercise (~30 s). *, † Significant difference ($P < 0.01$) from concentric and eccentric contractions at same relative intensity.

blood pressure response are illustrated in Fig. 4, *A* and *B*. When a subject performs dynamic leg presses, the increase in blood pressure at any point in time depends on the knee joint angle (Fig. 4*A*). Blood pressure is highest at a knee joint angle of 90° (the beginning position for raising the weight stack and the ending position for lowering it) and lowest at a knee joint angle of 170° (the position where the knee is extended or "locked out").

The effect of different joint angles on the blood pressure response to isometric contractions is illustrated in Fig. 4*B*. The strength curve is such that as knee joint angle is increased, strength increases as well. Despite significant increases in absolute force production in moving from a joint angle of 75 to 90 to 105°, the magnitude of the blood pressure response remains identical at the same relative force production.

Effect of muscle fatigue. The effect of muscle fatigue on blood pressure during a sustained isometric effort is illustrated in Fig. 5. When subjects attempted to maintain a maximal effort for 45 s, there was an immediate increase in systolic and diastolic pressures followed by a partial decrease over the first 3 s but not thereafter. In fact, pressure tended to increase with time subsequently. Force production, on the other hand, declined continuously with time, by >40% at the end of 45 s. Over this duration, heart rate increased linearly to ~170 beats/min.

DISCUSSION

Effect of muscle size and strength. We were successful in recruiting subjects who demonstrated a very wide range in quadriceps size and leg press strength, with an almost twofold difference between our smallest and largest subjects (Fig. 1, *A* and *B*). As previously noted (10), extremely high peak blood pressures occurred during this form of exercise. There was, however, a remarkable lack of correlation between peak pressure and muscle size despite a very wide range in size (Fig. 1*A*). Thus peak blood pressure for smaller subjects was the same as for larger subjects performing heavy weight lifting at the same relative intensity. Because of the high correlation between muscle size and muscle strength (5, 9), it was not surprising that peak blood pressure graphed against absolute

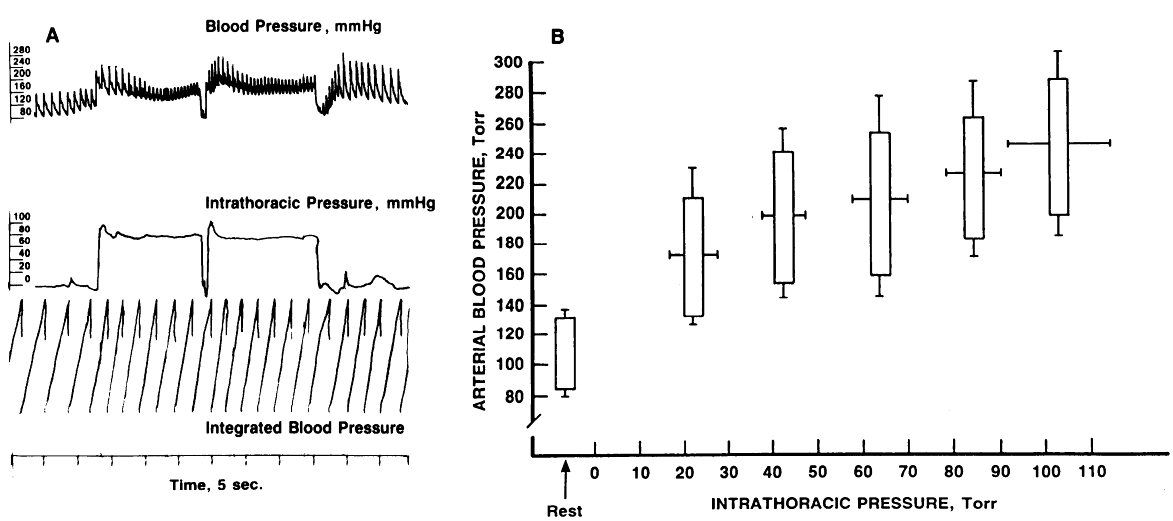

FIG. 2. *A*: actual trace for blood pressure and intrathoracic pressure while a subject, seated at rest, maintains a target intrathoracic pressure at 60% of his maximum Valsalva maneuver. Sudden drop in intrathoracic pressure indicates a breath. *B*: relationship between increases in intrathoracic pressure (caused by different intensities of Valsalva maneuver) and arterial blood pressure in 6 subjects. Values are means ± SD and represent Valsalva maneuvers at 20, 40, 60, 80, and 100% of maximum voluntary Valsalva pressure.

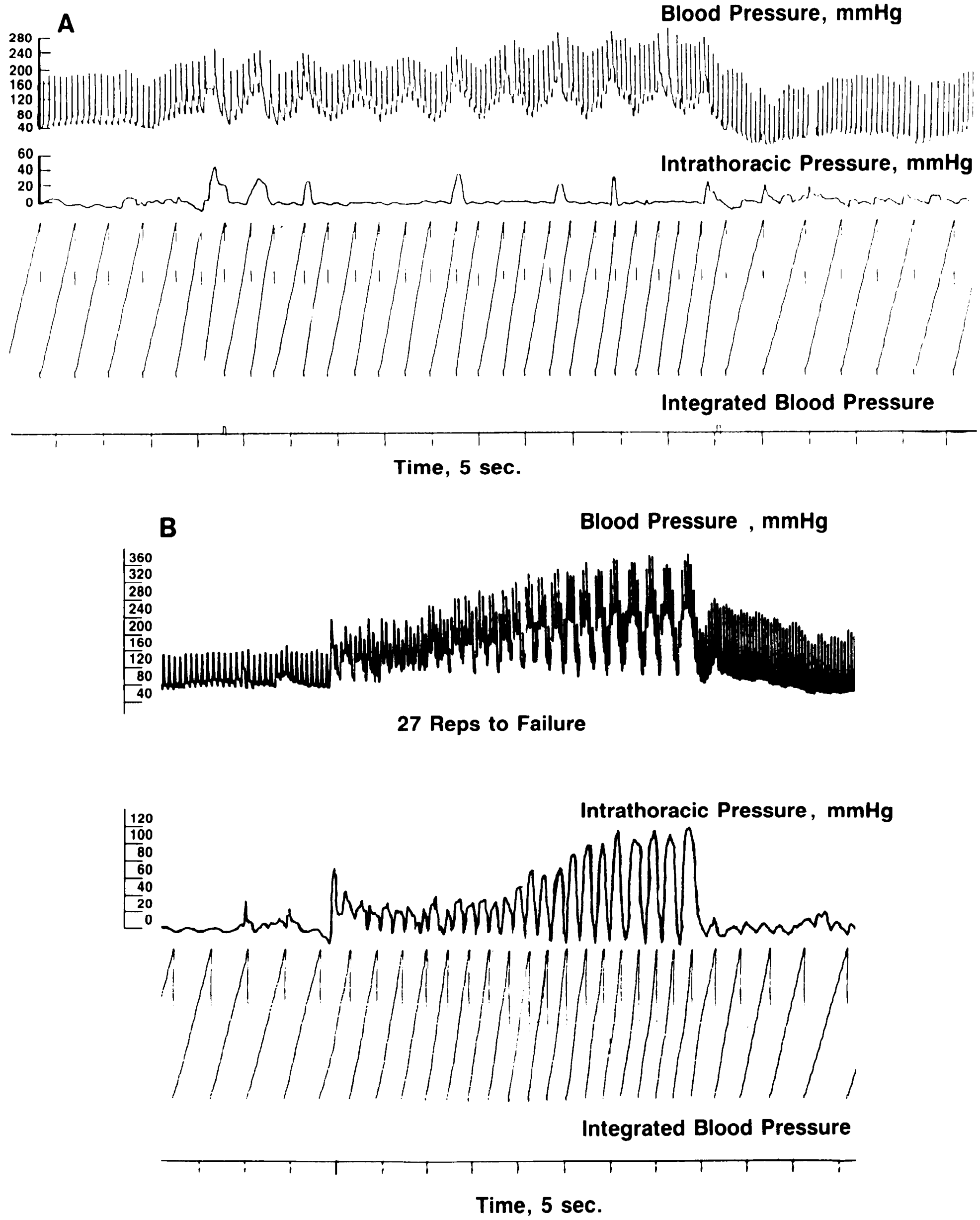

FIG. 3. Actual traces for blood pressure and intrathoracic pressure while a subject performs dynamic leg presses. *A*: weight represents ~75% maximum voluntary contraction (MVC), and subject only occasionally performs a Valsalva maneuver. *B*: weight represents ~85% MVC performed to failure, and subject finds it necessary to enlist a Valsalva maneuver with each repetition. Intensity of this Valsalva maneuver increases as subject approaches failure.

force production (i.e., the weight lifted for a 10 RM) revealed almost identical patterns (Fig. 1*B*). These data indicate that, during weight lifting, the magnitude of the blood pressure response is related to the intensity of the effort and is independent of absolute force production or interindividual differences in muscle size.

Effect of contraction type. It is well known that a muscle can develop more force in producing a maximum isometric effort than a maximum concentric contraction and more force in performing a maximum eccentric effort than a maximum isometric effort (6). Thus, by varying the contraction type, it is possible to dissociate the relationship between effort and actual force production. Table 1 shows that the blood pressure response is the same for the same relative effort despite large differences in absolute force production. Because differences in absolute force production would presumably alter output from the mechanically stimulated group III and IV afferents (12), we interpret our findings as indicating that the magnitude of the pressor response with this form of exercise is primarily (if not entirely) determined by the degree of central command or effort rather than feedback from the contracting muscles.

Effect of the Valsalva maneuver. The increase in intrathoracic pressure that occurs with a forceful Valsalva maneuver is immediately transmitted to the arterial tree, resulting in increases in both systolic and diastolic pressures (Fig. 2*A*). Initially this is an almost direct response (i.e., for each rise of 1 Torr in intrathoracic pressure, systolic and diastolic pressures rise ~1 Torr; Fig. 2, *A* and *B*). If the Valsalva maneuver is maintained, however, after ~3 s, systolic, diastolic, and pulse pressures begin to decline rapidly, apparently as a result of reduced diastolic filling caused by impaired venous return (Fig. 2*A*).

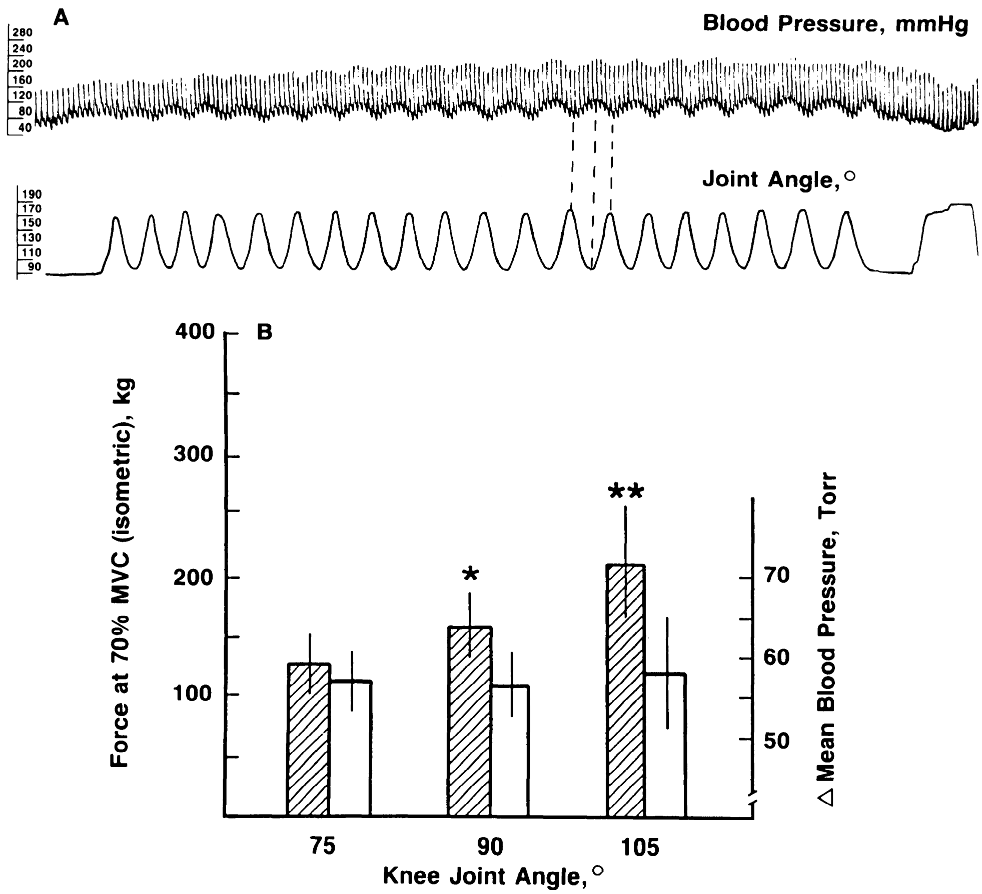

FIG. 4. Effects of different joint angles on blood pressure response to dynamic and isometric contractions. *A*: actual trace of blood pressure and knee joint angle (recorded from an elgon) while a subject performs leg presses at 65% MVC. With each repetition, joint angle goes from a starting position of 90 to 170° at full knee extension and back to 90° when weight has been lowered. *B*: increase in mean blood pressure that occurs when subjects perform sustained isometric contractions at 70% of their MVC at each of 75, 90, and 105° knee joint angles. Values are means ± SD for 6 subjects. *,** Significantly more force is produced at each higher joint angle, but increase in blood pressure is the same.

The Valsalva maneuver stabilizes the trunk, and during very heavy lifting subjects find it necessary to enlist a Valsalva or partial Valsalva to obtain the desired force production. The threshold above which the Valsalva maneuver becomes necessary varies somewhat for different muscle groups and between subjects but occurs at ~85% MVC. Similarly, when a resistance that initially may not require a Valsalva maneuver is lifted repeatedly until failure, an increasingly forceful Valsalva maneuver must be invoked as motor units progressively fatigue. During maximal dynamic lifting to failure, intrathoracic pressures may reach as much as 90-100 Torr (Fig. 3*B*) or up to 60% of that occurring during a maximum voluntary Valsalva maneuver.

The Valsalva maneuver is thus an integral component of heavy weight lifting and responsible for a major portion of the increase in blood pressure that occurs with this form of exercise. Although many weight lifting instructors counsel against performing a Valsalva maneuver during lifting, it probably acts as an important protective mechanism for the cerebral vasculature by elevating cerebrospinal pressure and thus reducing transmural pressure (2).

Effect of joint angle. The leg press movement involves the extensor muscles of both the hip and knee joints. The strength curve for this movement is such that the maximum force that can be produced increases dramatically as the knee is extended. Thus, if one begins a dynamic leg press at a knee joint angle of 90°, the weakest position in the strength curve, a greater effort is required to lift a given weight. As the lift proceeds and the knee approaches 170° (full extension), less effort is required to lift the same absolute weight; similarly, when the weight is lowered from 170° to the original position, the effort increases (Fig. 4*A*). Our finding that blood pressure is highest at a joint angle of 90° and lowest at 170°, increasing again as the weight is lowered to 90°, indicates that the magnitude of the pressor response depends on the degree of effort involved in the lift and not the absolute force of contraction. This is further supported by the blood pressure response to static exercise at different joint angles (Fig. 4*B*), where the same blood pressure is elicited at the same relative degree of effort despite large differences in absolute force production.

Effect of muscle fatigue. When a subject performs a maximum static effort, compressive forces are such that muscle blood flow is completely occluded (8). If the subject attempts to maintain a maximum effort, fatigue occurs and force output decreases. The mechanisms that might cause fatigue are many and complex (1, 4), and their discussion is beyond the scope of the present study. The result of the fatigue, however, provides an additional

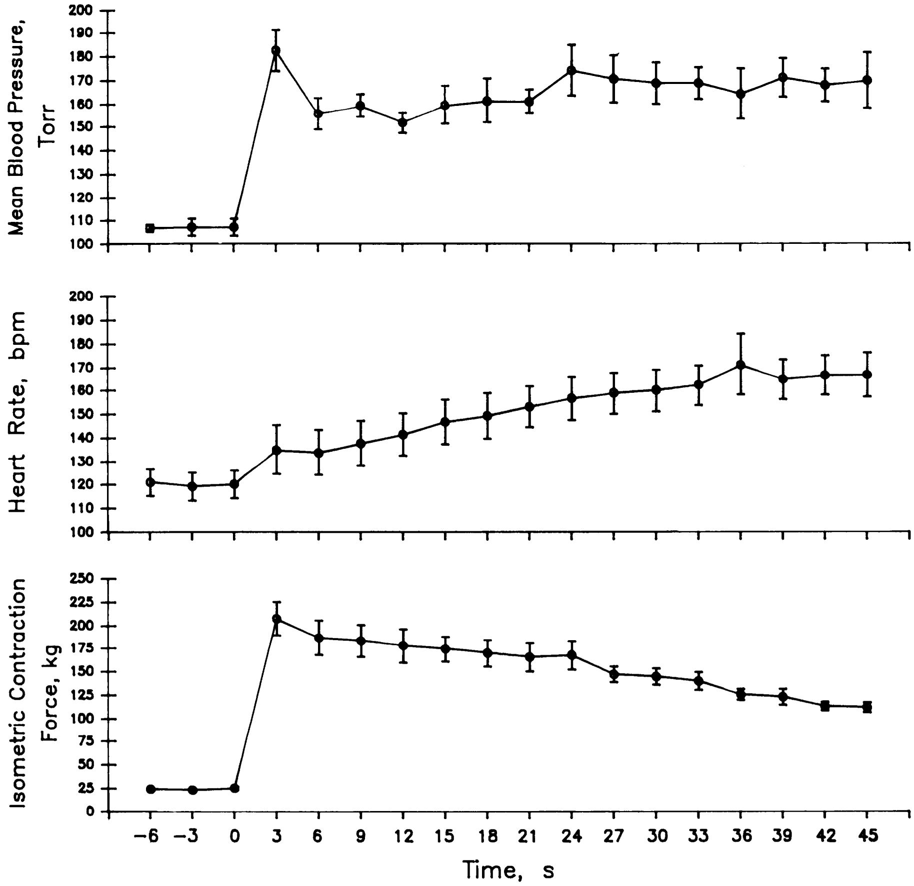

FIG. 5. Effect of muscle fatigue on blood pressure during a sustained isometric contraction. Subjects attempted to maintain a maximum contraction for 45 s. Values are means ± SD for 5 subjects calculated every 3 s.

model for uncoupling the relationship between effort or central drive and resultant force production.

Our finding that, after an initial overshoot, the increased blood pressure is maintained and even increases over time although absolute force decreases (Fig. 5) illustrates once again that it is central drive to the muscle that determines the magnitude of the pressor response. The tendency for blood pressure to increase over the latter part of the contraction is probably the result of increased cardiac output due to increased heart rate plus the probable recruitment of additional musculature in an attempt to maintain contraction force.

Summary. It has been suggested that the pressor response that occurs in response to heavy exercise is mediated by both a central component (drive from supraspinal areas of the brain to the muscle) and a peripheral or neural component (feedback from the muscle) that affects cardiovascular control centers. By manipulating such variables as the size and strength of the subjects, muscular fatigue, the type of contraction, and the joint angle for the contraction, we have succeeded in dissociating the normal relationship between central command (what goes into the muscle) and muscle force production (what comes out). In all instances it has been shown that the magnitude of the blood pressure response is dependent on the degree of effort or central command and not the actual force produced by the muscles.

Our data also confirm our previous findings (10) that extreme increases in blood pressure occur during heavy resistance exercise and that a brief Valsalva maneuver is an integral and unavoidable component of maximal or near-maximal contractions. The performance of a Valsalva maneuver exaggerates the increase in blood pressure that occurs with this form of exercise.

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