Central Hemodynamic Responses to Loaded and Unloaded ES-Induced and Voluntary Contractions of the Lower Leg

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ABSTRACT

Central hemodynamic responses to Electrical Stimulation (ES)-induced contractions were compared with voluntary contractions of the lower limb muscles in twenty subjects (legs). All subjects were healthy volunteers with normal venous capacitance and no reflux. Exercise protocols consisted of static and continuous loaded and unloaded lower leg muscle contractions produced by: 1) voluntary contraction (VOL), 2) ES-induced contractions of the gastrocnemius and tibialis anterior muscles (ES), and 3) combination of ES and VOL. A computerized impedance cardiograph measured Stroke Volume (SV), Cardiac output (CO), Cardiac Index (CI), Heart rate (HR), Mean Arterial Blood Pressure (MAP), and Total Peripheral Resistance (TPR). Changes in the above variables were statistically analyzed pre- and post each exercise protocol. Both static and continuous ES-induced contractions caused increases in SV, CO, and CI in comparison to pre-exercise values. However, these increases were significantly higher after continuous ES contractions when compared with VOL. TPR increased with static contractions and decreased with continuous contractions in all of the three treatment groups. The decrease in TPR could be secondary to vasodilatation produced by continuous ES. The increases in central hemodynamics were considered to be secondary to a decrease in blood pooling which in turn was secondary to the external stimulus of ES. The reduction in peripheral blood pooling, caused by increased blood flow via ES application, could be due to a mechanical “milking” effect on the lower limb venous bed during active contraction/exercise of the calf muscles. An increase in the pre-load of the heart may cause an increase in myocardial O2 uptake, and thus improved efficiency of the cardiovascular system. This system (ES) may be used efficiently to reduce blood pooling in paralyzed individuals.

I. INTRODUCTION

Blood flow to the skeletal muscle during and after volitional exercise is controlled principally by local metabolism [12]. The magnitude and frequency of active muscular contractions also affect the blood flow [11]. Because muscle metabolism increase in response to voluntary contractions, blood flow to the active musculature also increases. Central cardiovascular responses to static and continuous exercise has shown that greatest part of the oxygen uptake and cardiac output occurred after exercise, and that during the static exercise the blood flow through the muscles was occluded by the mechanical compression of the tensed muscle fibers [5]. The mechanical compression produced by calf muscle has been shown to be an effective means for reducing venous blood flow stasis and to move about a significant amount of venous blood back to the heart. This action of the calf muscle pump is called the peripheral heart.

In situations when active muscle contraction is not feasible (i.e., spinal cord injury, elderly, or during anesthesia) other means of activation of muscle contraction should be investigated. Electrical stimulation induced (ES) calf muscle contraction and activation of calf muscle pump function has been shown to increase blood flow in healthy subjects [2,10], during surgery[3], and in individuals with spinal cord injury [8].

Studies by Merlon and Naess, and Naes and Storm-Mathisen demonstrate that the tension elicited by maximal voluntary contraction and by electrical stimulation of the muscle were the same [6,7]. Because electrical stimulation produces muscle contractions the metabolism of the muscle being stimulated also increases. As a result, blood flow to a muscle should increase in response to electrical stimulation of muscle. Cardiac performance which may be determined by the interaction between central venous pressure and cardiac output, is to a large extent influenced by the peripheral circulation through active and passive redistribution of blood [13,14]. An increase in the muscle blood flow will increase in the pre-load of the heart which in turn may cause an increase in myocardial O2 uptake, and thus improved efficiency of the cardiovascular system. Previous studies demonstrated the mechanical effects of muscle pump and its effect on moving
the venous blood flow in the lower limbs. However, no study demonstrated the central cardiovascular responses to static and continuous exercises during ES induced, voluntary, or combination of both. Therefore, the purpose of this study was to determine whether electrical stimulation could produce alterations in the central blood flow due to electrically produced static and continuous contractions.

II. METHODS

Subjects:
Twenty legs of ten healthy volunteers (6 female, 4 male) with normal venous capacitance and no reflux were tested in this study. All subjects gave their written informed consent to participate in the study in accordance with the Institutional Review Boards of the University of Connecticut and Hospital for Special Care. None of the subjects had a history of disorders of the heart or circulation.

Instrumentation:
Computerized Impedance Cardiograph: Central hemodynamic responses of each subject were measured by a non-invasive computerized impedance cardiograph (CIC) Model CIC-1000.

Electrical Stimulator: An Empi Respond Select Dual Channel Neuromuscular Electrical Stimulator (Empi, Inc., St.Paul, MN) was utilized to provide surface electrical stimulation to each leg of all subjects. Self-adhesive reusable electrodes (5000 Series, Empi, Inc., St. Paul, MN) were applied to the lower extremities of each subject by the same tester according to the procedures described by Benton.

Procedure:
Each subject was randomly assigned to one of three exercise protocols on three different days in which the leg of each subject was tested separately. The protocols involved: Voluntary contraction (VOL), Electrical Stimulation-induced contraction (ES), and the combination of Electrical Stimulation-induced and Voluntary contraction (ES/VOL). Subjects were sufficiently rested prior to participation in each protocol.

Voluntary protocol: Each subject performed one or two maximum single loaded tiptoe contractions followed by ten continuos tiptoe contractions (repetitive loaded contraction) according to the testing procedure.

Electrical Stimulation protocol: The calf (gastrocnemius-soleus and tibialis anterior) muscles were stimulated to produce maximum plantar flexion without discomfort according to the testing procedure. One or two single unloaded electrically stimulated contractions were followed by ten continuos electrically stimulated unloaded calf muscle contraction.

Combined ES/Voluntary protocol: Each subject performed one or two maximum single loaded tiptoe contractions, followed by ten continuos tiptoe contractions (repetitive loaded contractions) according to the testing procedure. During each voluntary contraction, electrical stimulation was simultaneously administered at stimulation intensity as in the electrical stimulation protocol.

Testing procedure:
In a room at 22 to 24 C, each subject begins the protocol lying supine with the test leg relaxed and elevated to achieve minimum venous volume. Subjects then stand upright bearing full body weight upon the leg opposite the tested until maximum venous volume is achieved. One or two single tiptoe contractions were performed followed by resting in the standing position bearing full body weight on the opposite to the test leg. Continuos contractions started by asking the subjects to perform ten tip-toe exercises followed by standing on the opposite leg . The tests were completed by lying supine with leg elevated to reestablish minimum venous volume.

Measurements:
Central hemodynamic variables consisted of cardiac output (CO), stroke volume (SV), heart rate (HR), total peripheral resistance (TPR) and, mean arterial pressure (MAP). These variables were recorded for each subject during pre and post exercises at rest and before and after each tiptoe exercises.

III. RESULTS

There were significant increases in the ES group’s CO, CI, and SV when comparing pre and post exercises hemodynamics between the three groups. Voluntary contraction caused an increase of 10%, 10% and 14% in CO, CI and SV respectively and FES/VOL produced 7%, 7%, and 11% increases in these variables. Both static and continuos contractions produced increases in these three variables with the highest response in FES/VOL.
Resting pre-post exercises TPR significantly dropped in all three treatments, however these reductions were the highest for ES group. TPR also increased with static contraction and decreased with continuous contraction in all three treatments (figures 1-3). HR and MAP were not significantly altered during any of these exercises.

IV. DISCUSSION

Central cardiovascular responses to static contractions has shown that cardiac output, blood pressure and heart rate all increased considerably during this type of exercise, but after the stress the blood pressure and heart rate fell abruptly, while cardiac output and oxygen uptake rose further before returning slowly to the control levels [5]. In our study although there were increases in HR and MAP, these changes were not significant. In contrast, CO, SV and CI significantly rose even after discontinuation of exercise. These increases were significantly higher in the ES group. Early research by Barcraft and Millen showed that weak, sustained static contraction of the muscle at 10% MVC caused increased blood flow to the muscle during contraction without a further increase in the flow after exercise ceased. There were also reports that voluntary muscular contractions of 30% of MVC resulted in decreased blood flow during the contractions but that blood flow increased greatly after the contraction [1]. Based on the results of our study it appears that static contractions produced by ES and ES/VOL produced considerable muscle pump to move large amount of blood back to the heart as evidenced by high CO, SV and CI. Although we did not measure the level of the contraction produced, the strength of the contraction may be equal or higher than 30% MVC during static contraction. Richardson and Shewchuk reported that a postexercise increase in blood flow to the calf muscles was augmented by increasing the frequency and force of active muscular contractions [12]. Blood flow is also altered in response to electrical stimulation [11]. Randall et al. reported that greater hyperemia resulted from continuous electrical stimulation of a canine muscle than from active contraction of the muscle [4,9]. The results of our study support the above report since the highest CO, SV, and CI achieved were following ES-induced exercises followed by ES/VOL and VOL respectively. The reduction in TPR in ES groups could be the indication of reactive hyperemia in the muscle secondary to ES-induced contractions.

V. CONCLUSION

The increases in central hemodynamics were considered to be secondary to a decrease in blood pooling which in turn was secondary to the external stimulus of ES. The reduction in peripheral blood pooling, caused by increased blood flow via ES application, could be due to a mechanical “milking” effect on the lower limb venous bed during active contraction/exercise of the calf muscles. An increase in the pre-load of the
heart may cause an increase in myocardial O2 uptake, and thus improved efficiency of the cardiovascular system. This system (ES) may be used efficiently to reduce blood pooling in paralyzed individuals. The system may also be used to improve the muscle circulation.

VI. REFERENCES

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Supported by a Rehabilitation Grant from the Hospital for Special Care