LIPPINCOTT
WILLIAMS & WILKINS

EUROPEAN
SOCIETY OF
CARDIOLOGY

Original Scientific Paper

The effect of different intensity modalities of resistance training on beat-to-beat blood pressure in cardiac patients

Michel Lamotte, Georges Niset and Philippe van de Borne

Department of Cardiology, Erasme Hospital, Free University of Brussel, Belgium.

Received 3 June 2004 **Revised** 6 December 2004 **Accepted** 7 December 2004

Background **Resistance training has been introduced in cardiac rehabilitation to give more benefit than traditional training. Haemodynamic evaluation of cardiac patients to resistance training has generally consisted of continuous HR monitoring and discontinuous blood pressure measurements.**
Design and methods **Blood pressure (BP) and heart rate (HR) responses to resistance training were evaluated using continuous monitoring (Finapres) during low (four sets of 17 repetitions at 40% of the one-repetition maximum strength [1-RM]) and high intensity resistance training (four sets of 10 repetitions at 70% of 1-RM) on a leg extension machine in 14 patients who participated in a rehabilitation programme. Work volume was identical in the low- and high-level resistance training.**
Results **The HR and systolic blood pressure (SBP) during low intensity resistance training were always larger than during high intensity ($P<0.001$). Peak SBP increased from set 1 to set 3 and 4 during both low and high intensity resistance training ($P<0.05$). Peak HR was larger in set 4 (95 ± 11 bpm) than in set 1 only during low intensity resistance training (91 ± 12 bpm) ($P<0.05$). One-minute recovery periods did not allow a return to baseline HR and SBP during both low and high intensity modalities.**
Conclusions **The SBP and HR responses to resistance training are related to the duration of exercise. Sets with ≤ 10 repetitions of high intensity should be preferred to longer sets with low intensity. Pauses between exercise sets should exceed 1 min. Blood pressure should be measured during the last repetitions of the exercise set.** ***Eur J Cardiovasc Prev Rehabil*** **12:12–17 © 2005 The European Society of Cardiology**

European Journal of Cardiovascular Prevention and Rehabilitation 2005, **12**:12–17

Keywords: resistance exercise training, blood pressure, heart rate, cardiac rehabilitation

Introduction

Resistance training has been introduced in cardiac rehabilitation as a more effective method of increasing muscle strength. Resistance training was not recommended in the traditional endurance training of the 1980s.

Resistance training in cardiac rehabilitation relies on the concept of circuit weight training, during which the patient lifts moderate loads 10 to 15 times. The parameters that characterize a circuit weight training programme are number of exercise-stations, weight settings, number of repetitions of weight lifting, rest periods between exercise-stations, and number of circuits to be completed at each session.

According to the variety of resistance training protocols recommended, patients may lift weights between 40–80% of the maximal load that could be lifted only once [1–8] in the full range of motion. The patients were instructed to lift these moderate weights 8–25 times [1,4,6,7,9]. This may be repeated up to five times [3,7,9] after a recovery period ranging from 30 s to 3 min [1,4–7]. These modalities are now well accepted and are largely recommended [10,11].

Evaluation of the haemodynamic response to such circuit weight training in rehabilitation units has generally been

---

Correspondence and requests for reprints to M. Lamotte, Department of Cardiology 1E, 808 Lennik road, 1070 Brussels, Belgium.
Tel: + 32 2555 4256; fax: + 32 2555 4609;
e-mail: mlamotte@ulb.ac.be

1741-8267 © 2005 The European Society of Cardiology

limited to evaluation of continuous heart rate (HR) monitoring and discontinuous casual blood pressure (BP) monitoring. What is more, casual BP has often been measured within 10–30 s after exercise cessation [1–3,5,12–14].

The BP responses to various modalities of exercises have never been compared and these invasive studies have always been performed in isolated modality out of the cardiac rehabilitation context [15–22]. Thus, at the present time, a wide variety of circuit weight training modalities are being used in cardiac rehabilitation centres. However, because of the lack of studies on the BP and HR responses to various protocols of resistance training, recommendations remain empiric. Resistance training may induce large fluctuations in HR and BP, which may not be optimal in patients recovering from a serious cardiovascular event.

We therefore designed a study to test the hypothesis that both duration and intensity of muscle contraction are important determinants of the BP and HR responses to resistance training. We aimed thereby to demonstrate that identical work volume expressed in kilograms totally lifted, while using different exercise modalities, could minimize the haemodynamic burden of resistance training without compromising maximal muscle motor unit recruitment.

We evaluated the BP and HR responses during quadriceps extension work by using continuous HR and non-invasive finger BP monitoring during a low- and a high-level of resistance exercises on a leg extension machine in patients participating in a cardiac rehabilitation programme. The accuracy of finger BP recordings during resistance training was assessed against concomitant intra-arterial BP recordings in an additional set of experiments.

Patients and methods

Patients

Fourteen patients, aged 46–72 years participated to our study (height 172 ± 7.1 cms, weight 75.9 ± 11.8 kg). They had been included in the cardiac rehabilitation programme 1–3 months after bypass surgery ($n = 8$), percutaneous coronary angioplasty ($n = 3$) or valvular surgery ($n = 3$). Seven subjects received β-blockers, one received an angiotensin-converting enzyme inhibitor and one received a calcium antagonist at the time of the study. Left ventricular ejection fraction was > 45% in all patients (mean ± SD, 58 ± 9%).

Patients were studied with their daily medications, in the habitual environment of cardiac rehabilitation sessions, which therefore included the noise provided by other patients exercising on bicycle, treadmill or rowing machine.

Methods

The electrocardiogram was continuously monitored using a Hewlett Packard® monitor. Blood pressure was recorded beat-by-beat using a validated volume oscillometric method (Finapres, Ohmeda 2300, Englewood, Colorado, USA), which provides BP measurements similar to intra-arterial values both under resting conditions and during BP changes induced by laboratory manoeuvres [23,24].

The cuffed fingers were maintained at heart level throughout the entire recording procedure. Blood pressure and electrocardiogram measurements were recorded online on a Compaq 386/25 E (Compaq Computer Corporation, Houston, Texas, USA) for subsequent analysis.

Interventions

Resistance training on a leg extension machine was introduced in the training programme 2 weeks before the study. Each subject received detailed instructions on how to achieve a good body position throughout the movement, to perform the repetition in the entire range of motion and to avoid using the handgrips. In addition, subjects were requested to exhale during the most strenuous phase of the repetition and to inhale during the less strenuous phase of the repetition.

Low intensity resistance exercises on a leg extension machine combined four series of 17 repetitions at 40% of the one-repetition maximum (1-RM). High intensity exercise consisted of four series of 10 repetitions at 70% of 1-RM (Table 1). This combination of percentages of 1-RM used and the number of series and repetitions performed were designed to obtain a similar amount of kilograms lifted in total.

A metronome paced concentric and eccentric phases of each repetition, with cadence sets at 60 beats/min (2 s/repetition). Sixty-second pauses were observed between sets. The order of low and high intensity exercises were randomly assigned.

On the day of the study, ± 10 min after installation of the measurements devices, subjects were first asked to perform low resistance warm-up exercises. The maximum resistance against which one full range of motion could be performed (1-RM) was then searched. Changes in body position other than those directly resulting from the movement of the weight were not allowed during the 1-RM determination. Rest *ad libitum* was allowed between each trial in order to avoid muscle fatigue and to enable HR and systolic BP (SBP) to return to within the resting

Table 1 **Characteristics of the low and high exercise modalities**

Ex. modality	Number of set	Percentage of RM	Number of repetitions	Work duration	Rest duration
Low	4	40%	17	34 s	1 min
High	4	70%	10	20 s	1 min

RM, repetition maximum

values. Systolic BP never exceeded 220 mmHg during determination of 1-RM.

Finger BP accuracy study

Eight healthy volunteers aged 22–27 years participated in this study. They all underwent a 20 g intra-radial artery cannulation to facilitate direct invasive BP recordings. Finger BP was recorded on the contra-lateral arm while the hand was maintained at heart level. Subjects were subsequently asked to perform three sets of repetition at 75% of 1-RM, a set to exhaustion at 50% of 1-RM and a Valsalva manoeuvre. The SBP values used for this validation study were taken every 5 s.

Data processing and statistical analysis

The Ethical Committee of the Erasme Hospital accepted the study and each subject gave informed consent prior to inclusion.

Baseline systolic blood pressures were obtained by the Finapres before the low and high exercise modalities where adjusted to the auscultatory humeral SBP obtained by the classical arm cuff method. Data were collected 5–10 min after the installation procedure. For each subject, mean values of HR and SBP were calculated during the minute preceding each low and high intensity exercise, in order to provide baseline values for comparison with the BP and HR values obtained between each set of low and high exercise modalities.

The lowest HR and SBP values were determined before the beginning of the first set (P0), during the pauses between the sets of weight lifting, just before their beginning (P1, P2, P3) and 1 min after the last set (P4).

Systolic blood pressure varies considerably during the different phases of one contraction (concentric, isometric, eccentric) [15,15,21]. MacDougall [15] in particular demonstrated these big variations during slow resistive exercise using an intra-arterial measurement. The highest SBP values are obtained at the end of the concentric phase. In order to mirror this important variation, we fixed a mechanical pressure sensor to the distal leg contact with the quadriceps chair. This sensor provides impulsion's that mirrored the exact timing of the different movement phases. The concentric phase lasted 1 s; this corresponds, for a HR of 90 bpm, within 1–2 beats. For the rest, we therefore chose the lowest SBP immediately preceding the beginning of the effort (P0, P1, P2, P3 and P4). At the end of the set, the highest SBP immediately before the eccentric phase of the last repetition was chosen (S1, S2, S3 and S4). All results are expressed as the mean ± standard deviation.

Statistical evaluation was performed using the SPSS computer programme (SPSS Inc., Chicago, Illinois, USA) for analysis of variance with two factors (exercises and sets). When the *F*-ratio was significant, a modified *t*-test was used to compare paired values. In each exercise, sets 2, 3 and 4 were compared to set 1. Corresponding sets of low and high exercises intensity were also compared.

Results

Finger SBP measures adequately reflected concomitant changes in intra-arterial SBP elicited by three sets of repetition at 75% of 1-RM, a set to exhaustion at 50% of 1-RM and a Valsalva manoeuvre ($r = 0.82$, range 0.66–0.95).

Mean resting SBP and HR were comparable during the minute preceding the performance of low and high intensity resistance exercises. Systolic blood pressure was respectively 117 ± 15 and 126 ± 21 mmHg while the corresponding value for HR was 69 ± 10 and 69 ± 12 beats per minute, respectively.

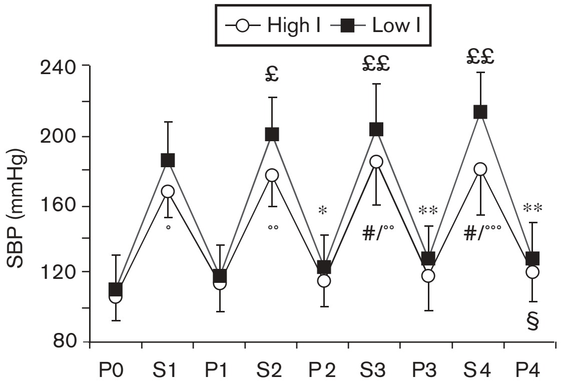
In all sets of low and high intensity resistive exercise, HR and SBP peaked during the last third of the set of weight lifting and decreased immediately and rapidly after cessation of exercise. Lowest HR and SBP occurred during the last 15 s of each pause observed between sets. The increases towards effort and the decreases during the recovery phases were both highly significant.

Peak HR and SBP differed ($P < 0.001$) between low and high intensity resistive exercises. The modified *t*-test between corresponding sets (S1, S2,…) of low and high intensity resistive exercises showed that HR and SBP, during low intensity resistive exercise, were always higher than the corresponding values during high intensity resistive exercise (Figs 1 and 2).

Peak SBP increased from set 1 to set 4 in low and high intensity resistive exercises and the differences reached a significant level ($P < 0.05$) when sets 3 and 4 were compared to set 1. Peak HR was significantly higher in set 4 (95 ± 11 bpm) than in set 1 (91 ± 12 bpm) but only during low intensity resistive exercise. The highest values for HR and SBP were thus recorded during the last set of low intensity resistive exercise (95 ± 11 bpm and 213 ± 25 mmHg respectively). Individual SBP never exceeded 250 mmHg during lifting.

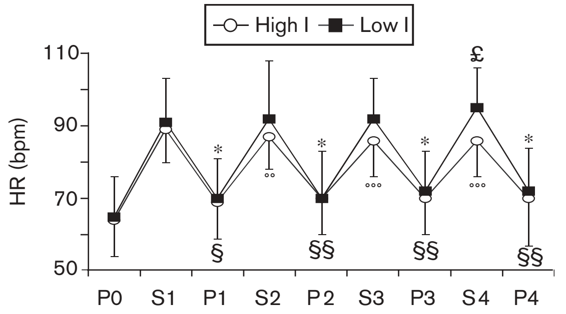
The lowest values of HR and SBP during pauses did not differ between low and high intensity resistive exercises

Fig. 1



Systolic blood pressure (SBP) during the pauses (P) and at the end of the series (S) from the first to the last series (0–4) in the low (■) and high (○) intensity resistive exercise modalities (mean ± SD). *Differences between pauses 1, 2, 3 and 4 (P1–P4) compared to 0 (P0), for the low modality (*$P<0.05$, **$P<0.01$). §Differences between pauses 1, 2, 3 and 4 (P1–P4) compared to 0 (P0), for the high modality (§$P<0.05$). £Differences between series 2, 3 and 4 compared to 1, for the low modality (£$P<0.05$, ££$P<0.01$). #Differences between series 2, 3 and 4 compared to 1, for the high modality (#$P<0.05$). °Differences between equivalent low and high series (°$P<0.05$, °°$P<0.01$, °°°$P<0.001$).

Fig. 2



Heart rate (HR) during the pauses (P) and at the end of the series (S) from the first to the last series (0–4) in the low (■) and high (○) intensity resistive exercise modalities (mean ± SD). *Differences between pauses 1, 2, 3 and 4 (P1–P4) compared to 0 (P0), for the low modality (*$P<0.05$). §Differences between pauses 1, 2, 3 and 4 (P1–P4) compared to 0 (P0), for the high modality (§$P<0.05$, §§$P<0.01$). £Differences between series 2, 3 and 4 compared to 1, for the low modality (£$P<0.05$). °Differences between equivalent low and high series (°°$P<0.01$, °°°$P<0.001$).

(Figs 1 and 2). The lowest values during pauses (P1, P2, P3, P4) were always higher than the lowest values in the minute preceding exercise (P0) during both low and high intensity resistive exercise. Statistical differences were reached for HR at P1, P2, P3 and P4 during low and high intensity resistive exercise while SBP was significantly higher at P2, P3 and P4 in low intensity resistive exercise and at P4 in high intensity resistive exercise.

Discussion

Our study reveals the new finding that, for a given work volume, the peak SBP and HR responses to low intensity resistance exercise are larger than during exercise at a higher level of resistance. Longer duration of exercise and more frequent weight lifting during low intensity resistive exercise are likely to explain these differences. Indeed, we observed a less marked increase ($P<0.001$) in HR and SBP when resistance exercise was performed at 70% of 1-RM in 20 s (10 repetitions) than when exercise was performed at 40% of 1-RM in 34 s (17 repetitions). The matching of total amount of kilograms lifted during the low and high intensity resistive exercise is one of the strengths of our study. In fact, the total work volume during low intensity resistive exercise was even slightly lower than during high intensity resistive exercise. Moreover, we validated the accuracy of our finger BP measurements against concomitant intra-arterial recordings in a separate study.

Our study suggest that resistance training in cardiac rehabilitation programme should prefer an increase in the load rather than an increase in the number of repetitions to obtain a progression in the total work volume.

Resistance exercise induces haemodynamic responses similar to isometric exercise [16,25]; HR and cardiac output increase without a decline in systemic vascular resistance. This produces a rapid increase in BP and imposes a greater pressure than volume load on the left ventricle [26]. This pressure response is directly related to the intensity [27–31]. Typically, fatiguing isometric contractions cause a progressive increase in BP and a modest increase in HR. The rate at which the BP increases during static contractions is dependent on the relative tension of the contraction. For any given muscle group, the greater the relative tension exerted, the faster the muscle will fatigue and the faster the BP will rise. Importance of muscle mass in the haemodynamic response to static contraction has been debated [15,28,32–34]. Nevertheless, Williams [34] suggested that muscle mass was not a determinant of the magnitude of the haemodynamic reflexes during fatiguing isometric contractions in man. Other authors thought that the haemodynamic responses during resistive exercise are associated with a volume overload as seen in dynamic exercise [8].

If some muscle simultaneously developed isometric contraction at different relative strengths, the increase in BP is determined by the way the muscle contracts with the more elevated relative strength (no summation effect). This indicates that the relative intensity (% RM) is the dominant factor compared to muscle mass used. The muscle mass used is important when the relative developed forces are equivalent [17,33].

It must be remembered that when a skeletal muscle performs static contractions at increasing percentages of its 1-RM, the intra-muscular mechanical compression eventually becomes such that muscle blood flow is hindered or stopped. Measurements of the point at which local blood flow becomes impeded by the contraction ranges from 40–60% of 1-RM and varies considerably between muscles and also studies. At values above 60–70% of 1-RM, blood flow is completely blocked [15,35–38]. The inadequacy of muscle perfusion triggers an increase in systemic BP capable of increasing the perfusion pressure to the exercising and fatiguing muscle. The precise metabolic stimulus that triggers the reflex increase in BP during static exercise is not precisely known and was not assessed in our study.

To our knowledge, systemic vascular resistance has never been measured during resistive exercise. Nevertheless, we may hypothesize that systemic vascular resistance response during resistance exercise is more similar to the response during static than during dynamic exercise due to the continuous contraction of muscle involved in resistance exercise. Indeed, the concentric contraction against the resistance is followed by an eccentric contraction to restrain the back phase of the movement. The intra-muscular mechanical compression of both concentric and eccentric contractions may stop or hinder muscle blood flow during exercise.

Our results emphasize that both duration and intensity of contraction have an impact on the pressure response. As for static exercise, a marked increase in SBP is an inevitable result of exercising for a long period of time, whatever the load. Heart rate also increases, although not as dramatically.

The progressive increase in haemodynamic responses from one set to the following can also be explained by the time. Higher levels of catecholamines have been observed during resistance training than during treadmill walking at the same level of oxygen uptake. Our study reveals that pauses between sets do not allow a complete return to resting levels of SBP. Succession of sets resulting in a progressive increase in catecholamines could explain these findings. Catecholamines increase the pressure response to resistance exercise through the increase in cardiac output by a greater tachycardia on the one hand and through the increase in the sympathetically mediated vasoconstriction, i.e., increase in the vascular resistance in both the active and non-active tissues, on the other.

The highest SBP recorded during our resistance exercises was obtained during 17 repetitions with a weight load of 40% of 1-RM. Values increased up to 185 ± 22 mmHg during the first set and up to 213 ± 25 mmHg during the fourth set, the difference being highly significant ($P < 0.01$). Those values must be compared to values obtained by Haslam *et al.* [18]. They obtained intra-arterial brachial BP recordings during weight lifting in eight cardiac patients. Over 10–15 repetitions at 40% of 1-RM, mean maximum SBP ranged from 170–186 mmHg depending on the specific exercise. These values are slightly lower than our values measured at the finger level. The higher number of repetitions in each set as well as the cumulating effect of the sets performed can explain the differences. The SBP values recorded during resistance exercise in our study are dramatically higher when compared to previous observations. However, these studies measured SBP only immediately after completion of a specified exercise-station during circuit weight training [1,3,12–14]. Our study supports previous data [19] suggesting that abrupt SBP decreases after cessation of exercise are probably responsible for these differences.

Our results further revealed that 60 s for pauses between series in each exercise did not allow a complete return to basic values of HR and SBP.

Healthy subjects are usually given rest periods of 15–30 s between stations. Indeed, in addition to improving strength and muscular endurance, circuit weight training seems to have the potential to contribute to the individual's cardiovascular conditioning if the rest between exercises are brief [39].

With cardiac patients, Kelemen *et al.* [1,12] proposed 30 s of rest before moving to the next station. Butler *et al.*, [2] proposed rest periods of 60 s to allow more complete recovery of HR and SBP between exercise stations. Some other recovery times have been proposed [3].

Except for a subset of cardiac patients with a good left ventricular function, it does not seem reasonable to impose short pauses between exercises that can contribute to an excessive burden to the myocardial function. Resistance training is usually added to an aerobic programme in cardiac patients. Therefore, the main goal of resistance training is to improve muscle strength whereas aerobic training programmes are more designed to improve cardiovascular conditioning.

Conclusion

In conclusion, the HR and SBP response to resistance training are not only related to the intensity but also to the duration of the exercise. Therefore, sets with ≤ 10 repetitions of high resistance should be preferred to longer sets with low resistance.

Pauses between sets should be ≥ 1 min and BP measurement must be done during the last repetitions of one set. Recommendations could be the following: in the initial sessions, patients should do 2–3 sets of 8–10 repetitions with weights corresponding to 30–40% of the predetermined maximum. Such low weights should cause minimal to no soreness and also increase the confidence of the patients to resistive training. The training regimen should then be raised gradually by increasing load rather than the number of repetitions. Finally, 3–5 sets at approximately 70% of the predetermined maximum should be obtained at each session.

References

1 Kelemen MH. Resistive training safety and assessment guidelines for cardiac and coronary prone patients. *Med Sci Sports Exerc* 1989; **21**: 675–677.

2 Bulter RM, Beierwaltes WH, Roger FJ. The cardiovascular responses to circuit weight training in patients with cardiac disease. *J Cardiopulm Rehabil* 1987; **7**:402–409.

3 Bulter RM, Palmer G, Roger FJ. Circuit weight training in early cardiac rehabilitation. *J Am Osteopath Assoc* 1992; **92**:77–89.

4 McCartney N, McKelvie RS, Haslam DR, Jones NL. Usefulness of weightlifting training in improving strength and maximal power output. *Am J Cardiol* 1991; **67**:939–945.

5 Crozier Ghilarducci LE, Holly RG, Amsterdam EA. Effect of high resistance training in coronary artery disease. *Am J Cardiol* 1989; **64**: 866–870.

6 Hunter GR, Wetzstein CJ, McLafferty CL, Zuckerman PA, Landers KA, Bamman MM. High resistance versus variable resistance training in older adults. *Med Sci Sports Exerc* 2001; **33**:1759–1764.

7 Pierson LM, Herbert WG, Norton HJ, Kiebzak GM, Griffith P, Fedor JM, *et al.* Effect of combined aerobic and resistance training versus aerobic training alone in cardiac rehabilitation. *J Cardiopulm Rehabil* 2001; **21**:101–110.

8 McKelvie RS, McCartney N. Weightlifting in cardiac patients. *Sports Med* 1990; **10**:355–364.

9 Pollock ML, Graves JE, Swart DL, Lowenthal DT. Exercise training and prescription for the elderly. *South Med* 1994; **87**:s88–s95.

10 Ades PA. Cardiac rehabilitation and secondary prevention of coronary heart disease. *N Engl J Med* 2001; **345**:892–902.

11 American College of Sports Medicine. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness in healthy adults and exercise and physical activity for older adults. *Med Sci Sports Exerc* 1998; **30**:975–991 and 992–1008.

12 Kelemen MH, Stewart KJ, Gillilan RE, Ewart CK, Valenti SA, Manley JD. Circuit weight training in cardiac patients. *J Am Coll Cardiol* 1986; **7**: 38–42.

13 Brown SP, Clemons JM, He Q, Liu S. Effect of resistance exercise and cycling on recovery blood pressure. *J Sports Sci* 1994; **12**:463–468.

14 Stralow CR, Ball TE, Looney M. Acute cardiovascular responses of patients with cardiac disease to dynamic variable resistance exercise of different intensities. *J Cardiopulm Rehabil* 1993; **13**:255–263.

15 MacDougall JD, Tuxen D, Sale DG, Moroz JR, Sutton JR. Arterial blood pressure response to heavy resistive exercise. *J Appl Physiol* 1985; **58**:785–790.

16 Lentini AC, McKelvie RS, McCartney N, Tomlinson CW, MacDougall JD. Left ventricular response in healthy young men during heavy intensity weight-lifting exercise. *J Appl Physiol* 1993; **75**:2703–2710.

17 McCartney N. Acute responses to resistance training and safety. *Med Sci Sports Exerc* 1999; **31**:31–37.

18 Haslam DRS, McCartney N, McKelvie RS, McDougall JD. Direct measurements of arterial blood pressure during formal weightlifting in cardiac patients. *J Cardiopulm Rehabil* 1988; **8**:213–225.

19 Wiecek EM, McCartney N, McKelvie RS. Comparison of direct and indirect measures of systemic arterial pressure during weightlifting in coronary artery disease. *Am J Cardiol* 1990; **66**:1065–1069.

20 Palatini P. Exaggerated blood pressure response to exercise: pathophysiologic mechanisms and clinical relevance. *J Sports Med Phys Fitness* 1998; **38**:1–9.

21 Narloch JA, Brandstater ME. Influence of breathing technique on arterial blood pressure during heavy weight lifting. *Arch Phys Med Rehabil* 1995; **76**:457–462.

22 Sale DG, Moroz DE, McKelvie RS, MacDougall JD, McCartney N. Comparison of blood pressure response to isokinetic and weight-lifting exercise. *Eur J Appl Physiol* 1993; **67**:115–120.

23 Imholz BPM, Wieling W, van Motnfrans GA, Wesseling K. Fifteen years experience with finger arterial pressure monitoring: assessment on the technology. *Cardiovasc Research* 1998; **38**:605–616.

24 Hildebrandt W, Schültze H, Stegemann J. On the reliability of the Penaz cuff during the systemic and local vasodilatation at rest and in exercise. *Eur J Appl Physiol* 1991; **62**:175–179.

25 Lewis SF, Snell PG, Taylor WF, Hamra M, Graham RM, Pettinger WA, *et al.* Role of muscle mass and mode of contraction in circulatory responses to exercise. *J Appl Physiol* 1985; **58**:146–151.

26 Hanson P, Nagle F. Isometric exercise: cardiovascular responses in normal and cardiac populations. *Cardiol Clin* 1987; **5**:157–170.

27 Ehsani AA, Heath GW. Non-invasive assessment of changes in LV function induced by graded I exercise in healthy subjects. *Chest* 1981; **80**:51–55.

28 Smolander J, Aminoff T, Korhonen I, Tervo M, Shen N, Korhonen O, *et al.* Heart rate and blood pressure responses to isometric exercise in young and older men. *Eur J Appl Physiol* 1998; **77**:439–444.

29 Hulten B, Thorstensson A, Karlsson J. Relationship between isometric endurance and fibres types in human leg muscle. *Acta Physiol. Scand* 1975; **93**:135–138.

30 Williams CA, Mudd JG, Lind AR. The forearm blood flow during intermittent hand-grip isometric exercise. *Circ Res* 1981; **48**:I110–117.

31 Kahn JF, Monod H. Modifications de la pression artérielle au cours du travail statique. *Arch Mal Cœur Vaiss* 1989; **82**:17–22.

32 Sagiv M, Hanson P, Besozzi M, Nagle F. Left ventricular responses to upright isometric handgrip and dead lift in man with coronary artery disease. *Am J Physiol* 1985; **55**:1298–1302.

33 Seals DR, Washburn RA, Hanson PG, Painter PL, Nagle FJ. Increased cardiovascular response to static contraction of larger muscle group. *J Appl Physiol* 1983; **54**:434–437.

34 Williams CA. Effect of muscle mass on the pressor response in man during isometric exercise. *J Physiol* 1991; **435**:573–584.

35 Sejersted OM, Hargens AR, Kardel KR, Blom P, Jensen O, Hermansen L. Intra-muscular fluid pressure during isometric contraction of human skeletal muscle. *J Appl Physiol* 1984; **56**:287–295.

36 Asmussen E. Similarities and dissimilarities between static and dynamic exercise. *Circ Res* 1981; **48(6, Suppl I)**: I3–I10.

37 Mitchell JH, Payne FC, Saltin B, Schibye B. The role of muscle mass in the cardiovascular response to static contraction. *J Physiol* 1980; **309**:45–54.

38 Shepherd JT, Blomqvist CG, Lind AR, Mitchell JH, Saltin B. Static exercise: retrospection and introspection. *Circ Res* 1981; **48**:I179–I188.

39 Gettman LR, Pollock ML. Circuit weight training: a critical review of its physiological benefits. *The Physician & Sportsmed* 1981; **9**:44–60.