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Muscular counterpulsation: preliminary results of a non-invasive alternative to intra-aortic balloon pump☆

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Abstract

Objectives: IABP is the most widely used form of temporary cardiac assist and its benefits are well established. We designed an animal study to evaluate a device based on muscular counterpulsation (MCP) that should reproduce the same hemodynamic effects as IABP in a completely non-invasive way. **Methods**: Six calves, 60 ± 4 kg, divided into 2 groups, in general anaesthesia, equipped with EKG, Swan-Ganz, pressure probe in the femoral artery and flow probe in the left carotid artery, received either IABP through right femoral artery, or muscle counterpulsation (MCP). MCP consists of electrically induced skeletal muscle contraction during early diastole, triggered by EKG and microprocessor controlled by a portable device. For each animal the following parameters were also considered: mean aortic pressure (mAoP), CO, CI, left ventricular stroke work index (LVSWI), systemic vascular resistance (SVR) and mean femoral artery flow (Faf). We did 3 sets of measurements: baseline (BL), after 20 (M20) and 40 (M40) min of cardiac assistance. These measurements have been repeated after 40 min of rest for 3 times. Results are expressed as mean ± SD. **Results**: Baseline values: mAoP, 76.51 ± 12 mmHg; mCVP, 11.5 ± 3 mmHg; CO, 5 ± 1 l/min per m^2; LVSWI, 0.77 ± 0.2 KJ/m^2; SVR, 1040 ± 15 dyn s/cm^{-5}; Faf, 75.5 ± 10 ml/min. IABP group: mAoP, 81.1 ± 6 mmHg; mCVP, 1 ± 0.1 mmHg; CO, 4.5 ± 0.7 l/min per m^2; LVSWI, 0.69 ± 0.2 KJ/m^2; SVR, 1424 ± 8 dyn s/cm^{-5}; Faf, 64.3 ± 3 ml/min. MCP group: mAoP, 60.1 ± 7 mmHg; mCVP, 23.6 ± 2 mmHg; CO, 4.8 ± 0.4 l/min per m^2; LVSWI, 0.69 ± 0.2 KJ/m^2; SVR, 608 ± 25 dyns/cm^{-5}; Faf, 92.3 ± 12 ml/min. **Conclusions**: MCP and IABP had the same effects on CO and LVSWI. Moreover, MCP reduced SVR and increased the peripheral circulation without requiring any vascular access nor anticoagulation therapy.

Keywords: Muscular counterpulsation; IABP; Cardiac assist; Ventricular dysfunction; Peripheral flow

1. Introduction

The intra-aortic balloon pump (IABP) is the most widely used form of temporary cardiac assist, and its benefits have been repeatedly acknowledged in patients with impaired left ventricular function [1–3]. IABP is frequently used in intensive care units for patients suffering from cardiogenic chock [4] and unstable angina [5]. It is also used in patients pre- and post-operatively [6,7] to support hemodynamic insufficiency. The principle timing of IABP is to inflate the balloon after aortic valve closure in early diastole and to deflate it just before the aortic valve opens in the succeeding beat. The inflation of the balloon in the early diastole displaces an amount of blood back towards the left ventricle (LV), increasing the pressure in the ascending aorta and thus enhancing coronary flow. Deflation of the balloon in late diastole reduces aortic pressure and consequently LV after-load for the succeeding ejection. This effect has been accounted for the improvement of LV oxygen demand and recovery of cardiac function related to the fall in wall stress [8]. However, IABP presents some limitations: it requires vascular access, anticoagulation and cannot be used in the presence of severe diseased aorta (e.g. aortic aneurysm and/or dissection) and aortic valve insufficiency. We developed a new method to potentially improve cardiac function at least as IABP does, overcoming many of IABP limitations.

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This method is called muscular counterpulsation (MCP) and consists of stimulating some skeletal muscles with an electric signal during diastole [9].

This study has been designed to compare the hemodynamic effects of MCP vs IABP in an animal model.

2. Materials and methods

Muscular CounterPulsation (CardioLa Ltd., Winterthur, Switzerland) consists of microprocessor-controlled stimulation of the skeletal muscles of the leg using trains of multiple biphasic electrical impulses applied during early diastole (Fig. 1). The device is provided with 3 ECG electrodes, 4 couples of stimulating electrodes for bipolar stimulation. Each electrode is a steel needle inserted about 3 cm into the muscular tissue and the distance between coupled electrodes is almost 3 cm. The stimulation signals consists of rectangular biphase fully balanced constant voltage impulses with a width (plus/minus) of 1 ms at a frequency of 200 Hz during a train duration of 75 ms set at 15–20 V amplitude. A rectangular impulse with a positive and negative amplitude is used. Muscle stimulation occurs when electricity passes between one active electrode and the neutral. ECG is used to trig the stimulation. The stimulation begins after the end of T wave.

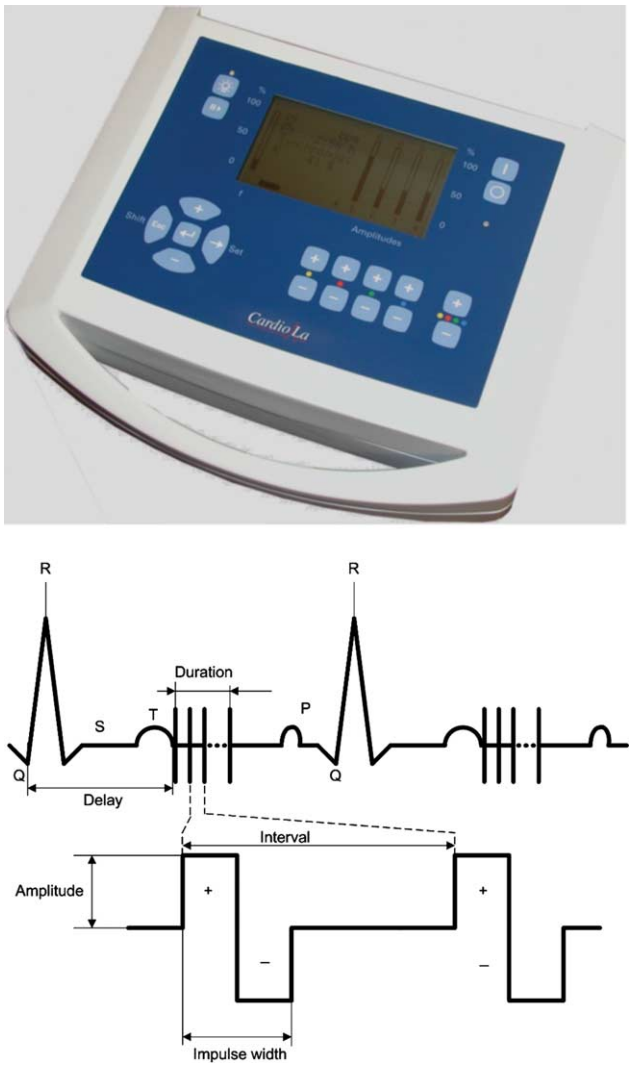

Fig. 1. Device for driving muscular contraction using trains of multiple biphasic electrical impulses applied during early diastole. ECG is the trigger. Muscle stimulation starts after the end of the T wave for a 1 ms width.

Muscles to be stimulated are chosen according to their mass; they have to be thicker than 3 cm. The thickness is manually assessed pinching the muscle between thumb and index finger.

Intra Aortic Balloon Pump (Datascope, XT 98, NJ USA) equipped with 40 cm^3 balloons at pumping cycles 1:1.

Flowmeter probes (Medi-Stim AS, Norway) perivascular flowmeter probes, size 4 and 5 mm, flow accuracy of 1%, resolution of 1 ml/min, flow sample rates 333 Hz.

The experiment was performed on 6 calves, 60 ± 4 kg in weight. All animals received human care in compliance with the European Convention on Animal Care and the study has been approved by our ethics committee.

2.1. Surgical technique

Calves were given ketamine 15 mg/kg, azaperon 0.5 mg and atropine 2 mg. General anaesthesia was induced and maintained with fluotane 2.5%. ECG, $SatO_2$ and expired CO_2 were continuously monitored. Both common femoral arteries and veins were exposed. Right carotid artery and jugular vein were exposed as well. Swan-Ganz catheter was inserted through the jugular vein into the pulmonary artery. Blood flow in the left femoral artery and vein and in the right carotid artery was measured. Arterial pressure was obtained from right femoral artery. Right femoral vein was used for perfusion.

Three calves received IABP through the right femoral artery. Three calves received MCP consisting of direct bilateral thigh muscles stimulation.

2.2. Experimental protocol

Animals were divided in 2 groups. For each animal we measured: heart rate (HR), mean aortic pressure (mAoP), central venous pressure (CVP), pulmonary artery pressure (PaP), wedge pulmonary artery pressure (WP), femoral artery (Faf) and vein (Fvf) and carotid artery flow (Caf). The following values were calculated: cardiac output (CO) with thermodilution method, cardiac index (CI), stroke index (SI = CI/HR), left ventricular stroke work index (LVSWI = SI × (mAoP − CVP) × 0.0022), systemic vascular resistance (SVR = (mAoP − CVP) × HR/CO). We did 3 sets of measurements: baseline (BL), after 20 (M20) and 40 (M40) min of cardiac assistance. These measurements have been repeated after 40 min of rest for 3 times (Fig. 2).

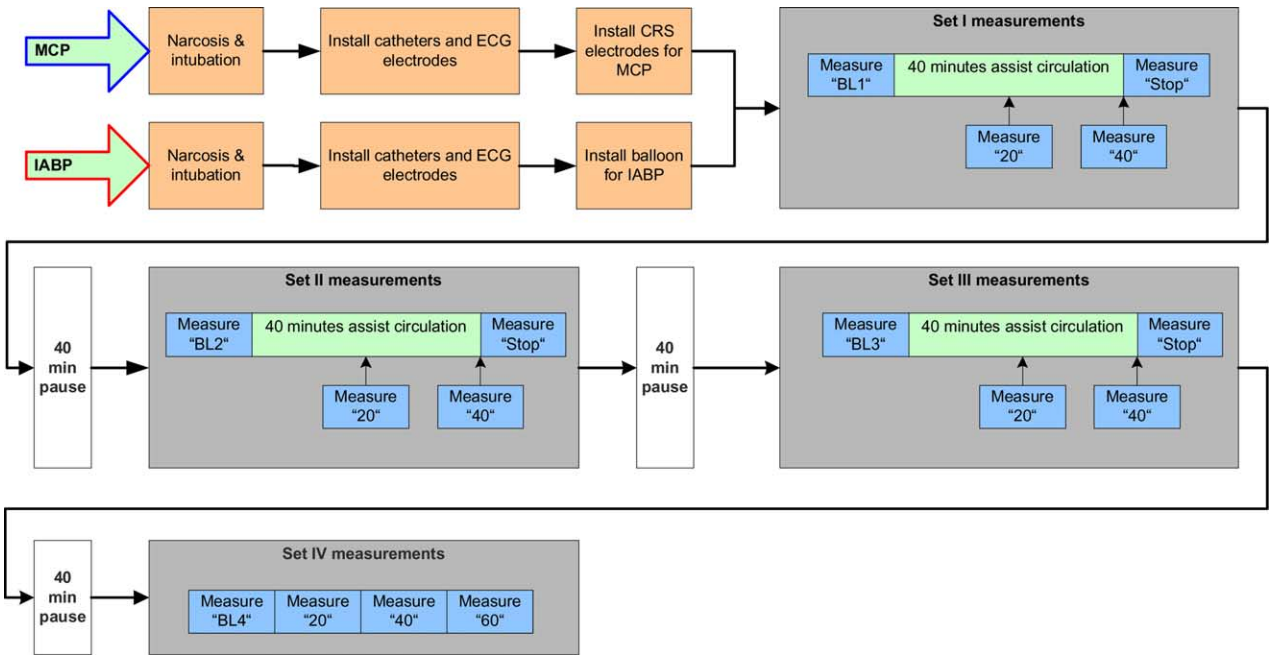

Fig. 2. Experimental protocol of MCP vs IABP. Animals were divided in 2 groups. For each animal we measured: mAoP, CO, CI, LVSWI (left ventricular stroke work index), SVR (systemic vascular resistance) mean femoral artery flow (Faf). We did 3 sets of measurements: baseline (BL), after 20 (M20) and 40 (M40) min of cardiac assistance. Those measurements have been repeated after 40 min of rest for 3 times.

2.3. Statistical analysis

Results are expressed as mean ± SD. For repeated measures, percent changes to baseline values were calculated. Comparisons between the two groups were carried out by an unpaired Student's *t*-test. A P value of <0.01 was considered to be significant.

3. Results

All animals completed the protocol without any adverse event. Each animal received 2.7 ± 0.7 l of saline infusion. One animal in the MCP group received dopamine 400 μg/min during the first rest period due to temporary hemodynamic instability. Detailed results are presented in Table 1.

4. Discussion

IABP is the most widely used form of temporary cardiac assist and its hemodynamic benefits are so well established that they could be considered as the reference. Another device has been developed to reproduce similar hemodynamic effects (external or peripheral counterpulsation) but its clinical value has not been clearly established and its use is still controversial [10]. This study has been designed to assess whether MCP could be an alternative to IABP at least in an animal model.

MCP is a new technique based on microprocessor-controlled stimulation of the peripheral muscles of the leg using trains of multiple biphasic electrical impulses applied during early diastole. This method is based on the assumption that ECG-triggered contraction of the muscles leads to a compression of peripheral veins and arteries associated with a change in pulse-wave propagation in terms of shortening of the pulse wave reflection distance. Similar improvements in cardiac function have been reported during intra-aortic balloon counterpulsation [11]. The correct timing of the stimuli seems to be essential, since no effect was observed during early and mid-systole or during late diastole. This can be explained by the timing of contraction of the peripheral muscles. Early systolic contraction induces an increase in after-load, whereas late diastolic contraction has no more hemodynamic effects. A rectangular impulse

Table 1
MCP vs IABP: hemodynamic parameters measured and calculated

	HR (b/min)	mAoP (mmHg)	mCVP (mmHg)	CO (l/min)	LVSWI (KJ/m^2)	SVR (dyn s/cm^{-5})	Faf (ml/min)	Fvf (ml/min)
Baseline	66 ± 5	76.5 ± 9	11.5 ± 3	5 ± 0.9	0.77 ± 0.1	1040 ± 15	75.5 ± 10	64 ± 12
MCP	63 ± 5	60.1 ± 7	23.6 ± 2	4.8 ± 0.4	0.69 ± 0.2	608 ± 25	92.3 ± 12	74 ± 10
IABP	67 ± 5	81.1 ± 6	1 ± 0.1	4.5 ± 0.7	0.69 ± 0.2	1424 ± 80	64.3 ± 30	62 ± 11
MCP vs IABP	ns	ns	$P < 0.001$	ns	ns	$P < 0.001$	$P < 0.001$	ns

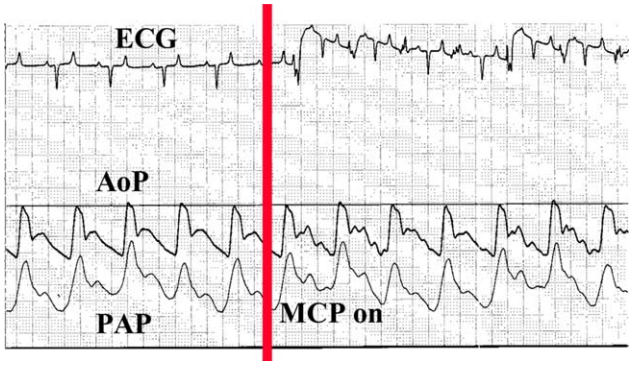

Fig. 3. Arterial pressure curb before and during MCP. Incremental pressure in the diastolic notch is irrelevant.

with a positive and negative amplitude is used to avoid electrolytic phenomena under the electrode that could occur after hours of stimulation.

MCP and IABP had the same effects on CO and LVSWI showing a cardiac unloading. However, when we look at the arterial pressure curb during MCP the incremental pressure in the diastolic notch is irrelevant (Fig. 3). Therefore, the mechanisms behind the hemodynamic effects of MCP are probably more complex than though. We found an SVR reduction and a femoral artery flow significantly higher than those associated to IABP and this could be one of the driving mechanisms of hemodynamic improvements. The mechanism behind the reduction in SVR could be similar to that associated to epidural spinal electrical stimulation. Low intensity spinal cord stimulation has been reported to enhance peripheral circulation through a transitory inhibition of sympathetic vasoconstriction [12]. We could speculate that the electric flow between the active and the neutral electrode produces a temporary sympathectomy either through a direct effect on spinal cord fibres or through the activation of neuro-endocrinal system. Further studies are indeed necessary to prove this hypothesis.

This study has some limitations, indeed. The animals we used were healthy and therefore the positive effect of cardiac assist on left ventricular function could be difficult to assess as demonstrated by the fact that there are no significant differences between baseline, MCP and IABP values of CO. Muscle fatigue, evaluated according to the amplitude of movement during stimulation, did not appear after 3 h stimulation but in all animals we had to increase the amplitude of the stimulation up to 20 V in order to keep the amplitude of the muscle movement constant. We can imagine that this phenomena could be the expression of muscle adaptation. Electrical muscle stimulation is well known from many applications to be harmless and without pain even at strongest muscle contraction level. However, during the stimulation, animals seem to have partial seizure and we imagine that patients could have experienced this as unusual sensation. Another limitation resides in the number of animals used in the study: six calves could be too small a group to reach a conclusive statistical analysis, but is definitely enough for a preliminary study.

5. Conclusions

MCP and IABP have the same effects on CO and LVSWI at least in this animal model. The driving mechanism of hemodynamic improvements associate with MCP seems to decrease SVR. Moreover, MCP increases the peripheral circulation without requiring any vascular access nor anticoagulation therapy.

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