Skeletal Muscle for Biomechanical Circulatory Support

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Abstract

Dynamic cardiomyoplasty, a surgical procedure that combines cardiac and plastic surgery with electrophysiology and biomedical engineering, was conceived to enhance cardiac performance by assisting ventricular contraction. Technically this procedure consists of placing a skeletal muscle flap around the heart and subsequently electrostimulation of the muscle in synchrony with ventricular systole. The growing interest in the use of skeletal muscle flaps in plastic and reconstructive surgery, stimulated our interest to develop this new technique. It has only been in recent years that functional electrostimulation of skeletal muscle has been possible. Interest in using skeletal muscle for circulatory support has increased accordingly.

Key words: Dynamic cardiomyoplasty, Biomechanical circulatory support, Cardiac assist device

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Human Feasibility

Functional electrical stimulation of skeletal muscle has already been used in many clinical applications such as recovery of denervated and reinnervated muscle, diaphragmatic stimulation via the phrenic nerve in respiratory paralysis, prevention of muscle disuse atrophy after major orthopedic surgery, and postural correction in scoliosis [20, 23, 28, 36].

Neuromuscular activity can be considered as the conversion of chemical energy into mechanical work. Muscular contraction involves generation of an action potential in a motor neuron, originating either from the central nervous system or artificially by electrical stimulation.

A subsequent series of biochemical reactions produce the energy required for muscle contraction. The concept of transforming skeletal muscle to enhance its resistance to fatigue, and its subsequent use as the energy source to repair or assist the failing heart is the principle on which dynamic cardiomyoplasty is based [6, 8].

Preclinical investigations showed that electrostimulated skeletal muscles can survive for a long time in an ectopic situation when the vascular and nerve supply were carefully preserved and when a progressive electrostimulation protocol was used [13].

The Choice of the *Latissimus Dorsi* Muscle

Early attemps of transplanting skeletal muscle onto the heart involved pectoralis muscle grafts in dogs for hypothetic repair of infarcted myocardial tissue and ventricular aneurysms [26]. Pectoralis muscle pedicle graft placed on the heart were shown to produce new vascularization of cardiac muscle [2]. Diaphragmatic pedicled grafts were also used for the treatment of human cardiac aneurysms [33].

Experimental use of electrostimulated diaphragm wrapped around the heart and around the descending aorta introduced the idea of biomechanical circulatory assistance [24]. Electrostimulated diaphragm flap to enlarge the right atrium and to assist ventricles was also reported [31].

The Latissimus Dorsi muscle flap (LDMF) was chosen for use in dynamic cardiomyoplasty due to the anatomy of its neurovascular pedicle which allows its transposition into the thoracic cavity, without functional sequelae to the shoulder and arm [18, 32, 39, 40]. We were able to carry out cardiomyoplasty without cardiopulmonary bypass, facilitated by the close proximity of the Latissimus Dorsi muscle to the heart, the length of its neurovascular bundle and that the muscle mass itself stretches without problem. The flap provides a large mass of contractile tissue and can be moulded around the heart (Fig. 1). The presence of the LDMF in the chest does not alter respiratory function [4].

Mobilization and Transposition of the LDMF

The LDMF can be mobilized and rotated on its neurovascular axillary pedicle into the chest cavity through a window created by partial resection (6 cm) of the anterior arc of the second rib. It is then, subsequently, secured around the heart. The position of this chest wall window allows the LDMF to be easily transposed to the heart [32, 40].

Electrostimulation of the muscle flap in a manner synchronous with ventricular contraction is delivered by an implantable Cardio-Myostimulator (Medtronic model SP 1005) via intramuscular electrodes. A sensing intramyocardial lead completes the electronic device [14].

The following problems concerning the skeletal muscle viability and trophicity have been encountered during the development of cardiomyoplasty techniques.

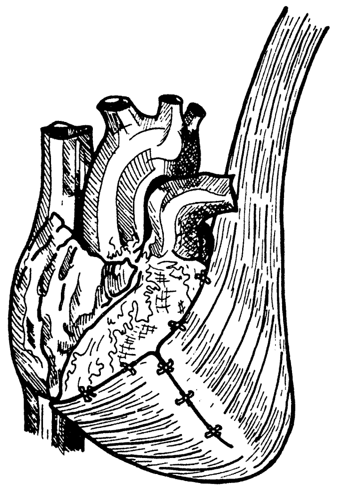


Figure 1. Dynamic cardiomyoplasty surgical technique.

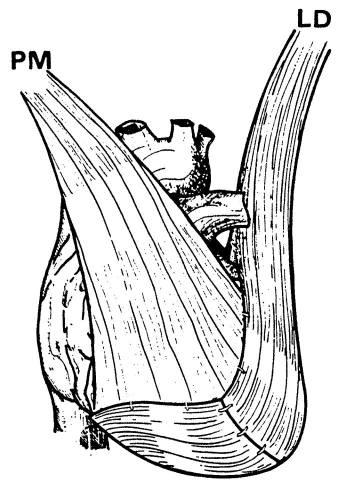


Figure 3.Double-flap cardiomyoplasty, using the left latissimus dorsi (LD) and the right pectoral muscle (PM).

A) The surgical mobilization of the LDMF results in the division of collateral circulation arising from intercostal vessels to the distal part of the muscle mass. Sometimes, there is a degree of regional ischemia and congestive venostasis. New collateral vessels however do develope postoperatively between the LDMF and the epicardial surface as well as between mediastinal structures.

B) Candidates for cardiomyoplasty present low cardiac output. This of course is suboptimal for creating viable pedicled muscle grafts [41].

C) Muscle disuse atrophy is generally present in patients with severe chronic heart failure.

D) The use of inotropic agents in the postoperative period (skeletal muscle vasoconstrictors) is potentially detrimental to the LDMF viability.

E) In order to assist ventricular systole optimally, solid adhesions from the LDMF to the heart surface must develope.

For these reasons the LDMF is left undisturbed for 2 weeks after cardiomyoplasty. After this period the stimulation protocol begins with single pulses and low amplitude, using a heart to muscle contraction ratio of 2:1. The definitive muscle stimulation (using burst of impulses) is programmed after the second postoperative month [12].

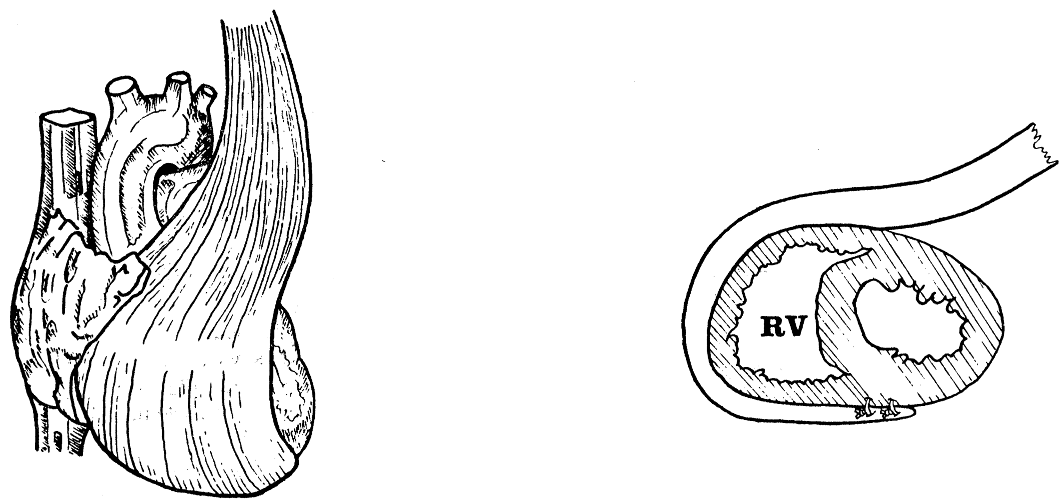


Figure 2. Right ventricle (RV) cardiomyoplasty. Anterior-posterior wrapping using the left latissimus dorsi or the left pectoral muscle.

Systolic Contraction of Skeletal Muscles

During the last years, a considerable amount of biomedical research on the adaptative capabilities of electrostimulated skeletal muscles has been performed [7, 34, 37]. These studies showed that striated muscle changes its physiologic, biochemical and ultrastructural characteristics in response to different patterns of chronic electrical stimulation.

In order to assist the heart with an electrostimulated LDMF we developed the implantable electronics and leads for muscular cardiac assistance and then the program of electrical stimulation which has overcome the problem of skeletal muscle fatigue. This has allowed us to achieve chronic synchronized graft contraction with the heart's systolic contraction. Specially designed neuromuscular LDMF pacing electrodes were manufactured (Medtronic model SP 5528). These electrodes allow selective muscle bipolar stimulation, that results in strong contractions of the entire LDMF. The cathode is placed in close proximity to the distribution of the main nerve branches into the muscle. Chronic muscle stimulation by burst of impulses at a cycle of 25% stimulation time (duration of stimulation 185 ms, frequency in the burst: 30 Hertz) and 75% recovery time (555 ms) imitate a systolic/diastolic cycle, without significant skeletal muscle fatigue or muscle fiber degeneration.

Hemodynamic Benefits of Cardiomyoplasty

The goal of skeletal muscle transformation by chronic electrostimulation is to make it suitable for chronic assistance. The cardiomyoplasty procedure, is designed to prolong and improve the quality of life of patients with severe and irreversible chronic cardiac insufficiency by improving ventricular contraction and limiting cardiac dilatation. Increased ventricular volume is one of the most powerful predictors of decreased survival in patients with heart disease [35].

Contractility and dilatation are the most important of several factors contributing to the deterioration of ventricular function in the evolution of congestive heart failure. Cardiomyoplasty allows the LDMF to augment cardiac workloads chronically. No evidence of skeletal muscle fatigue has been demonstrated. Long-term hemodynamic studies showed no tendency of the LDMF to compress or constrict the heart.

Reports of experimental models of myocardial failure [19, 21, 25, 30, 38] clearly show the benefit of dynamic cardiomyoplasty on ventricular function.

Ventricular Wall Substitution

Substitution cardiomyoplasty involves the partial replacement of a ventricular wall after large aneurysm or tumor resections [3, 9]. This reconstructive approach includes the closure of the ventricular defect by a patch of autologous pericardium as neoendocardium, covered by a chronically electrostimulated Latissimus Dorsi muscle flap (LDMF) as neomyocardium. Thrombosis at the muscle-blood interface and the risk of an interfascicular LDMF hematoma are avoided by the pericardial patch [16].

In an experimental protocol using this technique, a normal cardiac output was preserved for periods exceeding 6 months, after left or right partial ventricular wall substitution [15].

The first successful clinical substitution cardiomyoplasty (full-tickness partial left ventricle replacement) was performed at the Broussais Hospital on July 1st, 1987, after extensive ischemic aneurysm resection [13]. Five successful similar clinical cases follow this early surgical experience.

Pectoral Muscle for Right Ventricle Cardiomyoplasty

In selected cases right ventricle cardiomyoplasty may be indicated after sternotomy has been performed and the heart exposed. In these cases Latissimus Dorsi cardiomyoplasty is difficult to perform since it requires previous dissections of the LDMF. For this purpose we have investigated the use of electrostimulated pectoral muscles (easily approached during the patient supine position) to be applied to the right ventricle.

In 5 goats the left pectoral muscle was mobilized by a median vertical incision. The acromiothoracic neurovascular pedicle was carefully dissected and preserved. Two pacing electrodes (Medtronic SP 5528) were implanted in the proximal part of the muscle mass. The pectoral muscle was then transported into the chest by a window created by resecting the anterior arc of the first rib. Humeral and clavicular insertions were divided and through a median sternotomy a right ventricular cardiomyoplasty was performed, wrapping the heart in a counterclockwise fashion (anterior-posterior wrapping) (Fig. 2). The muscle was then electrostimulated using synchronous 30 Hertz burst of impulses.

Anatomically the lenght and size of the left pectoral muscle were adapted to cover the right ventricle. Electrostimulated muscles contracted vigorously during the experiments. Muscle fiber orientation was the appropriate to assist right ventricular function. Hemodynamic benefits were documented.

Right ventricle cardiomyoplasty could be clinically performed using electrostimulated left pectoral or latissimus dorsi muscles.

Double Flap Cardiomyoplasty

Dynamic cardiomyoplasty was conceived to assist ventricular contraction in patients with dilated cardiomyopathy. In cases with severe heart dilatation, complete wrapping is impossible due to insufficient latissimus dorsi muscle mass. In order to obtain a complete dynamic wrapping an electrostimulated right pectoral muscle (RPM) or a right latissimus dorsi can be used to supplement the left LDM.

In an experimental study 8 adult alpine goats received a dynamic cardiomyoplasty as follows: 1) Left LDM mobilization and transposition into the chest after reducing its size by resecting the distal edge in order to obtain an incomplete cardiac wrapping. 2) RPM mobilization and transposition into the chest. 3) Cardiac wrapping with both the LDM and the RPM (Fig. 3). Synchronic electrostimulation of both muscles was postoperatively undertaken. Hemodynamic studies (CO, LV and RV pressures) were performed during cardiomyoplasty and 6 months later.

At 6 months cardiac failure was induced by administration of high-dose propranolol (3 mg/kg IV). Comparative data were recorded with (ON) and without (OFF) electrostimulation of both muscles at each stage, and without RPM stimulation.

Hemodynamic studies showed that double flap cardiomyoplasty offers an increased circulatory support when compared with single muscle cardiomyoplasty (Fig. 4). This hemodynamic improvement was more pronounced in the model with heart failure.

Pectoral muscle could be used concomitantly with the LDM in cases of extremely dilated hearts in order to obtain optimal

Figure 4. Hemodynamic study following double-flap cardiomyoplasty. Increase of left ventricular pressure (LVP) during latissimus dorsi and pectoral muscle stimulation (arrows). The diastolic function is also improved by increasing the "diastolic suction" (stars). RAP: right atrial pressure, ECG: electrocardiogram.

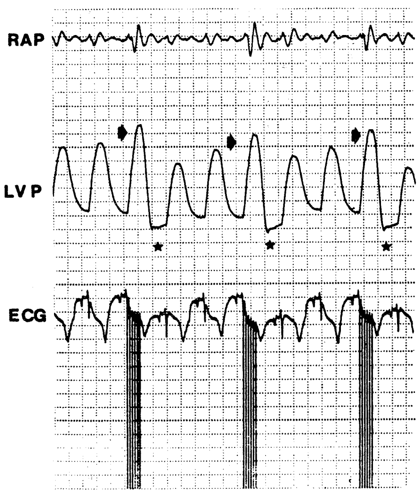


Table I

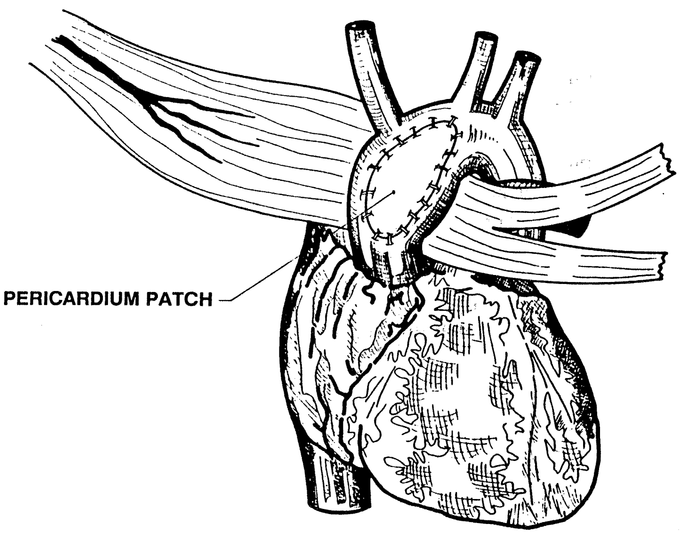
SKELETAL MUSCLE CIRCULATORY ASSIST DEVICES

I) CARDIAC ASSIST PUMPS: - ATRIAL CARDIOMYOPLASTY - VENTRICULAR CARDIOMYOPLASTY
II) EXTRA CARDIAC ASSIST PUMPS: - BIOLOGICAL: Dynamic aortomyoplasty - PROSTHETIC: Skeletal muscle extra-aortic ventricles

dynamic cardiomyoplasty procedure, or secondarily to supplement an insufficient result of LDM cardiomyoplasty.

Atrial Cardiomyoplasty

Atrial cardiomyoplasty may be applicable in congenital heart diseases. This technique involves the fixation of the left LDMF over the right atrium. The aim of atrial cardiomyoplasty is the "ventricularization" of the atrium, in order to improve its output after atriopulmonary connections. The left LDMF is brought over the right atrium so that a larger contact area between the free right atrial wall and the muscle can be obtained. Orientation of muscular fibers provides better hemodynamic results than when compared to those obtained by the right LDMF [11].



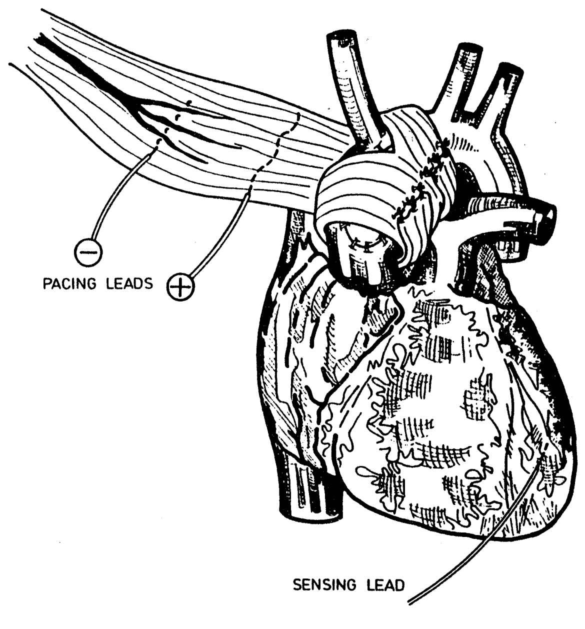


Figure 5. Dynamic aortomyoplasty: skeletal muscle diastolic counterpulsation around the enlarged ascending aorta.

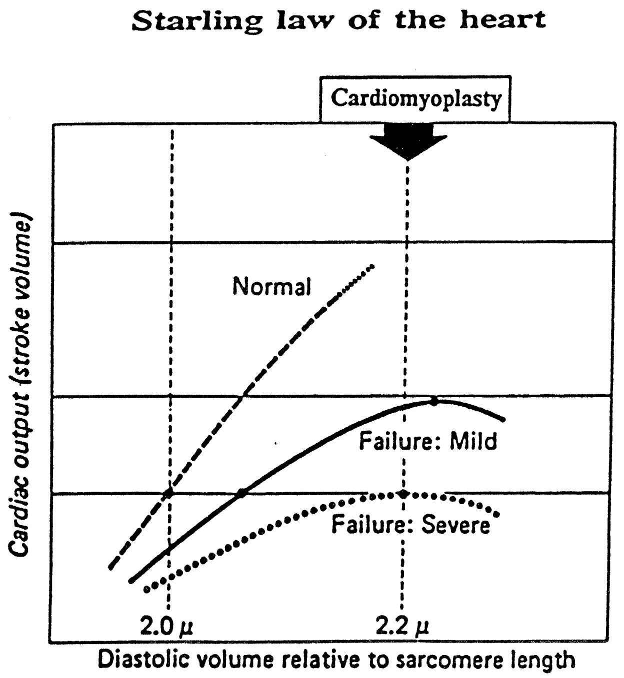


Figure 6. Interpretation of the effect of cardiomyoplasty on ventricular end-diastolic volume, according to the Starling law of the heart.

Experimental studies [17] showed that LDM electrostimulation restores a pulsatile pressure pattern in the pulmonary artery and increases the cardiac output. Atrial cardiomyoplasty could improve the long-term results of the Fontan procedure e.g. in cases of tricuspid atresia or single ventricle, and may allow atriopulmonary connections in patients with atrial fibrillation or incipient pulmonary vascular hypertension.

Dynamic Aortomyoplasty

Aortomyoplasty is a surgical procedure that consists of wrapping the latissimus dorsi muscle flap around the ascending aorta (AA) to compress it, with electrostimulation of the muscle mass in each diastole [10].

The native AA, enlarged by a pericardial patch, becomes a secondary ventricular chamber (Fig. 5).

In 8 goats, a right LDMF was transferred to the thoracic cavity by removal of the 2nd rib. In 4 of these goats the diameter of the AA was enlarged by a pericardial patch. The AA was wrapped with the LDMF and electrostimulated in a counterpulsation manner, using a diastolic pulse generator. LDMF diastolic counterpulsation was performed using bursts of 30 Hz, with a delay from the R wave adjusted to provide optimal diastolic augmentation. Hemodynamic studies were performed during unassisted and assisted cardiac cycles (1:2) in the basal state and after acute heart failure induced by the administration of high doses of propranolol.

Diastolic AA counterpulsation delivered by the dynamic aortomyoplasty procedure resulted in a significant hemodynamic augmentation both in basal state conditions and after induced cardiac failure, and principally in the group with aortic enlargement.

Aortomyoplasty represents a new hemocompatible contractile chamber in the ascending aorta. The native aortic valve serves to close its afferent orifice. Counterpulsation is effectively performed at the proximity of the coronary artery ostia. The "diastole" of the aortomyoplasty chamber (occurring during Latissimus Dorsi relaxation) decreases the left ventricular afterload.

Conclusions

Dynamic cardiomyoplasty involves two of the most important recent scientific advances in the fields of electrophysiology and cardiac surgery. The first is the recent advance in muscle physiology which makes possible the transformation of skeletal muscle fibers to a fatigue resistant state [1, 27]. The second is the development of burst pulse generators which allow synchronous stimulation of skeletal muscle with ventricular systole or diastole. These two advances have resulted in the development of biomechanical circulatory assist techniques.

Dynamic cardiomyoplasty was conceived to assist the failing heart by wrapping it with a chronically electrostimulated Latissimus Dorsi muscle flap. The aim of cardiomyoplasty is both the functional and anatomic replacement or augmentation of akinetic or dyskinetic ventricular regions. Its effects on ventricular performance are due to the increased pump function and to the limitation of cardiac dilatation.

Cardiomyoplasty preserves a physiological myocardial sarcomere lenght by limiting ventricular end diastolic volume. In that way it follows the Starling law of the heart (Fig. 6).

Cardiomyoplasty is indicated in patients with chronic cardiac insufficiency refractory to appropriate medical therapy. Indication for cardiomyoplasty is principally dilated cardiomyopathy of ischemic or idiopathic origin.

Hypertrophic cardiomyopathy is not an indication to cardiomyoplasty because of the inability of the LDMF to compress the ventricular cavity.

Clinical experience at Broussais involves 40 patients operated on between January 1985 and March 1991. Multivariate analysis of factors influencing operative outcome reveals that age, early surgical experience, associated surgical procedures, biventricular heart failure, and patients in terminal stage, are predictors of unfavorable outcome. Surviving patients are in mean NYHA functional class 1.4 (preoperative 3.3, $p < 0.05$). One patient developed severe postoperative hepatitis after cardiomyoplasty. He lost 1/5 of his body weight and had generalized muscular hypotrophy. Six months later he remained in functional class IV of the NYHA. Orthotopic heart transplantation (OHT) was undertaken on December 3, 1990. Technically the procedure was performed without difficulties and the patient is alive and well 4 months following OHT.

In conclusion cardiomyoplasty is an efficient technique to assist patients with severe chronic cardiac failure. It offers an improvement of the functional class and of the exercise capacity as well as a reduced pharmacological support [5, 22, 29]. Operative and postoperative mortality was reduced with experience, better patient selection, and improved surgical technique. Cardiomyoplasty does not preclude the future use of other surgical procedures such as heart transplantation, ventricular assist devices, or artificial heart.

Aortomyoplasty offers a new horizon and hope for the treatment of profound refractory chronic left ventricular failure [10]. This extracardiac technique could be indicated in patients with left ventricular cardiomyopathies and extremely dilated hearts, when a mitral valve insufficiency is associated, or in patients with previous cardiac operations. Furthermore, aortomyoplasty could be viewed as a complementary technique in patients who have undergone left ventricular cardiomyoplasty and in whom supplementary hemodynamic support is necessary. We think that this periaortic counterpulsation assisting device represents a very important step forward and should be further investigated.

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