MINIREVIEW

Skeletal Muscle as a Myocardial Substitute

(43974)

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Abstract. **During the last several years, there has been intense worldwide interest concerning the use of skeletal muscle as a form of cardiac assistance. For over 10,000 people in the United States diagnosed each year with irreversible heart failure, the 1-year mortality approaches 50%. This comes despite recent advances in medical therapy, heart transplantation, and the artificial heart program.**

Because of the limitations of these treatments in terms of effectiveness, cost, and availability, we have used a different approach for cardiac augmentation. Skeletal muscle is shaped into the form of a pumping chamber and then used to aid the function of the failing myocardium. Another approach is cardiomyoplasty, where the latissimus dorsi muscle is wrapped around the heart and stimulated to contract in synchrony with the patient's failing myocardium. More than 500 patients have undergone cardiomyoplasty worldwide. These two areas of investigation represent the principle methods for skeletal muscle cardiac assistance. [P.S.E.B.M. 1996, Vol 211]

History

The use of skeletal muscle for cardiac assistance is not a new idea, the first clinical use probably being in 1931 when DeJesus used skeletal muscle to replace a traumatic defect in the heart (1). Beginning in the late 1950s, investigators began reporting experiences with skeletal muscle used in laboratory animals in a variety of configurations to augment cardiac function. Their results were disappointing, with muscle fatigue being the major obstacle (2–4).

Salmons and Vrbova subsequently discovered that chronic exogenous electrical stimulation would effect a change in muscle fiber characteristics from fast-twitch (Type 2) to slow-twitch (Type 1). When stimulated over a period of 6 weeks, the muscles in these experiments showed an increase in capillary density, enzymes of oxidative metabolism, and mitochondrial volume fraction (5, 6). All of these changes resulted in an increased resistance to fatigue.

A second obstacle involved the blood supply of the muscle itself. With the division of collaterals required for muscle mobilization, muscle ischemia develops. Mannion and colleagues have demonstrated that a 3- to 4-week vascular delay period is needed before the blood supply will return to near normal levels (7).

Methods of Use

Skeletal muscle may be used to either assist the systolic function of the heart or to augment diastole.

Systolic Augmentation. Systolic augmentation may be achieved by several methods.

Reinforcement technique. Cardiomyoplasty refers to the technique in which skeletal muscle is wrapped around the ventricles and stimulated to contract synchronously with the native heart (Fig. 1 and

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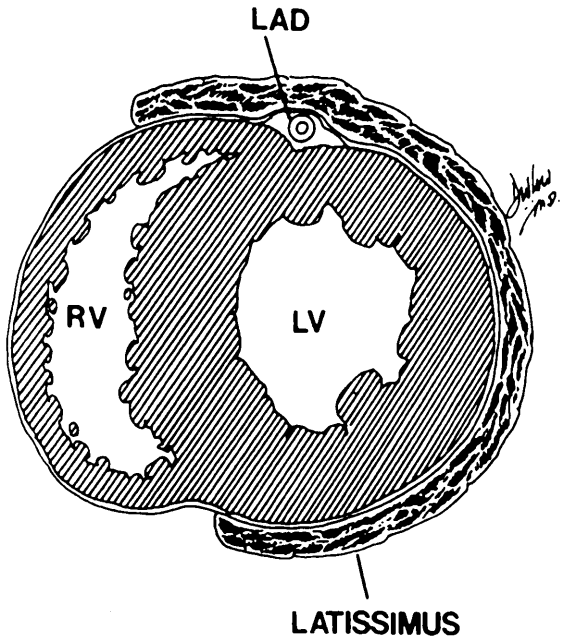

Figure 1. (original[2] Fig. 1) Drawing of cross-sectional representation of the muscle graft as it overlies the left ventricle (LV) and a portion of the right ventricle (RV). LAD, left anterior descending coronary artery (reprinted with permission from Circulation **78**[suppl 111]:111–182, 1988).

2). The first clinical application of this procedure was reported in 1985 (8), and although this procedure has been performed in over 500 patients worldwide, the mechanism of clinical improvement is uncertain. There have been many reports that failed to show a consistent improvement in hemodynamic performance. Carpentier and colleagues, however, were able to show an improvement in ventricular function at 9 months (cardiac output, +21%; peak blood velocity, +40%–80%; and stroke volume +98%–102%) (9). Nakajima has suggested that the muscle acts more as an "active" support for the myocardium and prevents further ventricular dilation (10). His group showed that ventricular contractility improved and myocardial oxygen consumption decreased in animals undergoing cardiomyoplasty. However, they found the presence of the muscle itself was enough to cause the changes; that is, in most animals there were no differences in the hemodynamic values observed with the myostimulator on or off.

One report (11) did show an increase in survival in a group of 13 patients. The 18-month actuarial survival of this group was 80%, which compared favorably to a similar control group of 16 patients who showed a survival of 31% for the same period. Although this study was not randomized, the two groups were comparable. In a recent update extending this group's experience to 5 years, they showed that although there was modest improvement in hemodynamic performance, as shown by an increase in ejection fraction from 19.8% ± 3% to 23.9% ± 7.2%, as well as significant changes in stroke index, arterial pressure, pulmonary artery wedge pressure, and left ventricular stroke work index at 6 months, these values steadily declined to preoperative values at 5 years (12).

Skeletal muscle ventricle. In our laboratory, skeletal muscle ventricles (SMVs) are constructed by wrapping the latissimus dorsi muscle around a Teflon mandrel to create a muscle pouch or tube (Fig. 3) (13). The mandrel is removed after a period of 3–4 weeks. This allows for recovery of blood supply, formation of adhesions between the layers of the muscle wrap, and development of a smooth inner lining. The SMV can then be used in a variety of configurations.

Right Heart Bypass. In laboratory animals, skeletal muscle has been used to supplant the native right ventricle. With this procedure, cannulas were placed in the inferior and superior vena cavae such that all systemic venous return was routed through the SMV which pumped into the pulmonary artery. With the SMV switched off, blood flowed passively through the

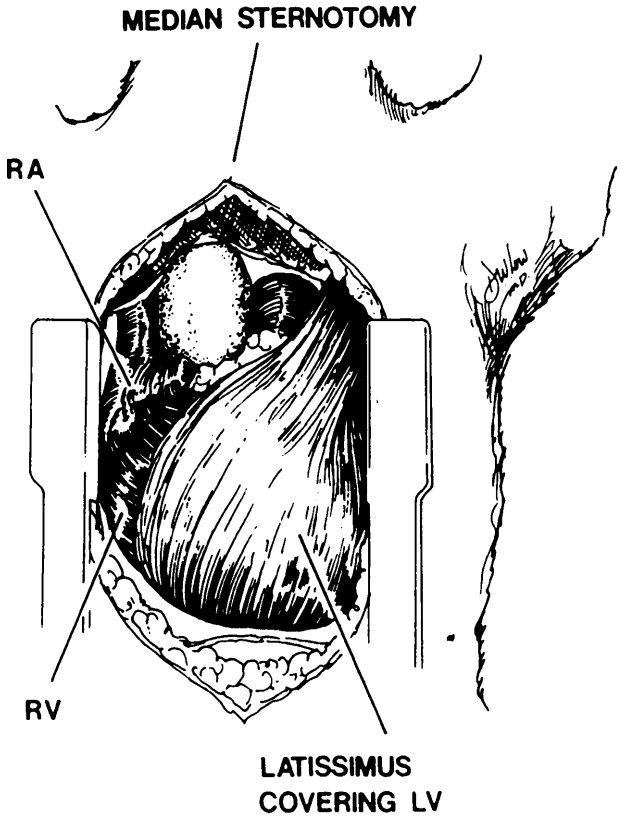

Figure 2. (original[2] Fig. 2) Drawing of muscle graft covering the canine heart as depicted through a midline sternotomy (reprinted with permission from Circulation **78**[suppl 111]:111–182, 1988).

[2] ("Original" refers to the original review (Anderson DR, Pochettino A, Hammond RL, Stephenson LW. Skeletal muscle as a myocardial substitute. Proc Soc Exp Biol Med **197**:109–118, 1991), of which this article is an update.

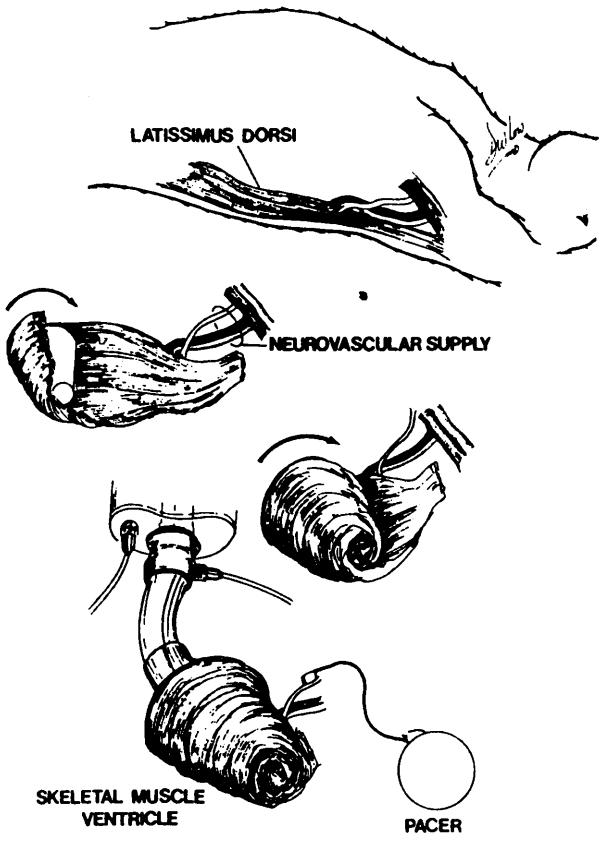

Figure 3. (original[2] Fig. 4) Construction of the SMV (reprinted with permission from The Journal of Thoracic and Cardiovascular Surgery **92**:734, 1986).

SMV and connecting conduits to the lungs, and the animal became hypotensive. On activation of the SMV, there was an immediate rise in blood pressure. Aortic blood flow was maintained at approximately 80% of normal over a 4-hr period (14).

Although these initial studies showed promise, it has been demonstrated that SMV function is substantially improved if the preload is higher than that which can be achieved by the venous system alone. In an effort to exploit the higher pressure generated by the right ventricle, a configuration was devised whereby the SMV was placed in series between the right ventricle and pulmonary artery, as depicted in Figure 4. The pulmonary artery was then ligated proximally to obligate flow through the SMV, thus using the right ventricular pressure as the SMV preload. Acute studies performed at 1 and 4 hr demonstrated an increase in cardiac output of 27% at 1 hr and 30% at 4 hr with the SMV on versus off. Systemic arterial pressure showed an increase at 1 hr by 12% and at 4 hr by 13%. Peak pulmonary pressure also increased by 35% at 1 hr and by 37% at 4 hr. Further studies showed that effective assistance may be obtained for periods of up to 16 weeks (15).

Left Heart Bypass. There have been two additional configurations of SMV constructed for systolic augmentation that have been evaluated in our laboratory. These have focused on using the pressure generated by the left heart to serve as preload for the SMV. The first system involves using two valved conduits, the first between the left atrium and the SMV, and the second between the SMV and aorta (16). The SMV then contracts in cardiac diastole. In acute 3-hr experiments, left atrial pressures remained in the range of 14 to 16 mm Hg and the SMVs were able to pump between 21% and 27% of the cardiac output. We have not tested this model in the circulation long term, however, because this model would likely need higher filling pressures to function optimally. It is possible that with a stable left ventricular failure model where filling pressures would be higher, this configuration would function effectively for longer periods.

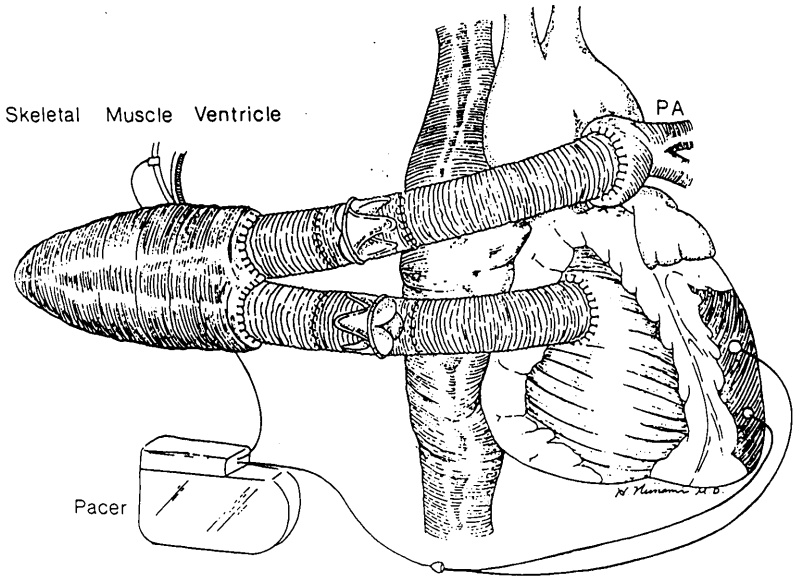

Figure 4. Diagram of an SMV connected in the right heart circulation. The proximal pulmonary artery is ligated to obligate flow through the SMV.

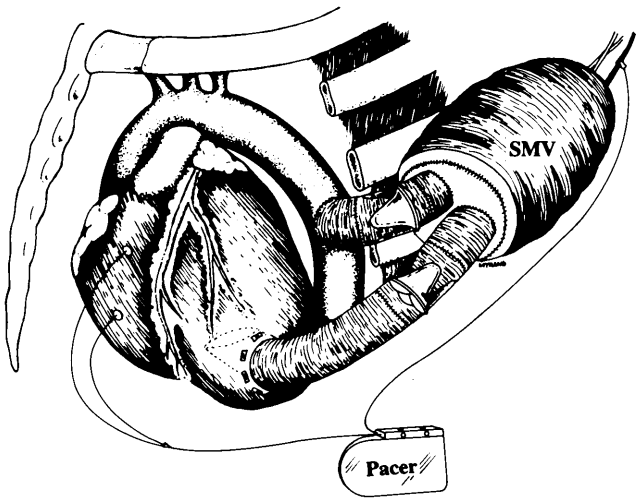

Figure 5. SMV in the LV apex-to-aorta configuration with two valved conduits. The afferent conduit connects the LV apex to the SMV, and the efferent conduit connects the SMV to the descending aorta.

In an effort to exploit the higher filling pressures of the left ventricle for SMV preload, a configuration of left ventricular apex to aorta has been developed (Fig. 5) (17). In addition to the improved preload, there is likely to be improved blood flow in the muscle layers of the SMV compared with diastolic augmentation because the SMV cavity pressure is equal to left ventricular (LV) end-diastolic pressure during a portion of the cardiac cycle (18, 19). Acute 3-hr experiments have demonstrated a significantly lower systolic tension-time index with the SMV on versus off. The endocardial viability ratio was also significantly increased, showing an improvement of 68%, 66%, 62%, and 63% at initial measurement and at 1, 2, and 3 hr, respectively with the SMV on versus off. Figure 6 shows a representative pressure tracing from one animal at the time of operation.

There was little improvement in cardiac output noted in this experiment, however it was demonstrated that the SMV pumped 47% of the systemic blood flow, substantially reducing the oxygen requirement of the left ventricle. Stevens and colleagues have shown a substantial increase in systemic blood flow of 31% using an SMV LV apex-to-aorta configuration of their own design in animals that were in heart failure, compared with the increase in 6% seen in our study (18). Our most recent efforts are focusing on developing this configuration into a chronic model, with one dog having survived over 2 months with such a functional SMV (unpublished).

Diastolic Augmentation. Aortic diastolic augmentation, better known as aortic counterpulsation, has been used clinically for the last 19 years to support the failing heart. This has been done with the use of the intraaortic balloon pump. Skeletal muscle ventricles also offer a potential for clinical application in this area.

Intraaortic balloon pump. This is the most common method in use, especially in the setting of heart failure after open heart surgery. This device is inserted through the femoral or iliac artery and positioned in the descending thoracic aorta. Helium gas is used to inflate the balloon, which is synchronized via a cardiac monitor to expand during cardiac diastole. The device typically remains in place for 2 or 3 days but has been used for longer than 1 month. This counterpulsation works in three ways to benefit the heart. First, blood is pumped as the balloon expands and forces blood in both directions up and down the aorta. Second, since the coronaries are perfused during diastole, there is an

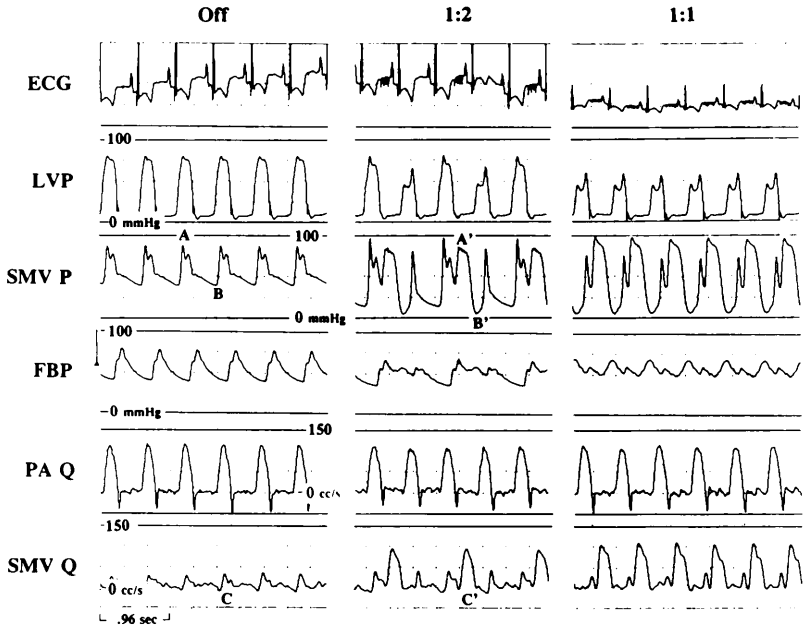

Figure 6. Hemodynamic recordings obtained from an SMV at the time of surgery with SMV contraction off (left) and contraction on at a 1:2 or 1:1 ratio with the heart. ECG, electrocardiography; LVP, left ventricular pressure; SMVP, SMV pressure; FBP, femoral arterial pressure; PAQ, pulmonary flow; SMVQ, SMV flow.

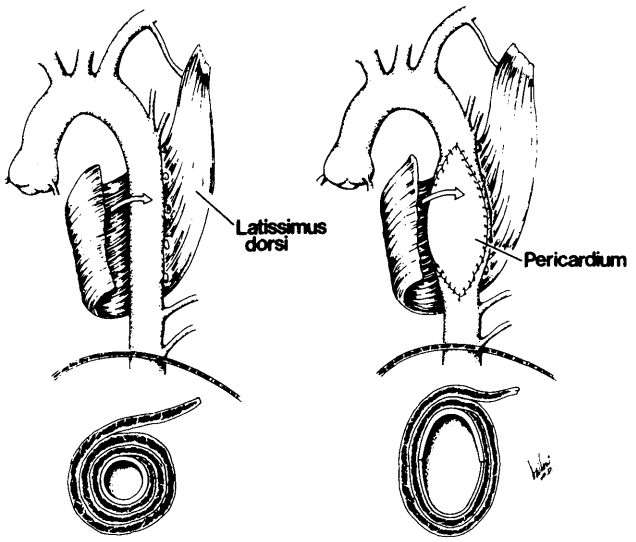

Figure 7. (original[2] Fig. 3) The muscle is fully mobilized and introduced into the thorax where it is wrapped around the descending aorta after division of a number of intercostal branches (left). The aorta is enlarged to increase the volume of blood that is compressed. Pericardium or any flexible material can be used (right).

increase in coronary blood flow. Finally, the deflation of the balloon during systole results in a decreased afterload, decreasing the work requirement of the failing left cardiac ventricle (20).

Aortomyoplasty. Kantrowitz, who was a pioneer in the use of the balloon pump, and colleagues originated work in aortomyoplasty, and in 1959 described wrapping the diaphragm around the descending aorta (2). This system uses the animal's own aorta as the inner lining, which should avoid the risk of thrombosis. The main drawback is that the volume of blood displaced depends on the length and diameter of aorta encompassed. To address this issue, Chachques and colleagues have advocated the use of a pericardial patch to enlarge the native aorta (Fig. 7) (21, 22). Acute and chronic studies have been encouraging, however this technique could be associated with substantial morbidity in the setting of an atherosclerotic or calcified aorta.

The effectiveness of the descending aortomyoplasty procedure has been demonstrated in acute (23) and chronic (24) studies. Additionally, Lazarra and colleagues (25) have shown that the improvement in hemodynamics is comparable to that achieved with the intraaotic balloon pump. They identified an improvement in diastolic relaxation time and considered this an important component. One major obstacle to the clinical application of this model may be the degree of mobilization of the aorta required for the procedure. In animal studies, this has required the ligation of several sets of intercostal arteries. Although paraplegia has not been reported in the animal studies, this may be due to a more developed collateral blood supply in these models. Cernaianu and colleagues have attempted to address this issue and recently published a study where they divided the muscle such that it could be wrapped around the aorta in a way that avoids dividing the intercostals (26). They showed the muscle in these animals had a significantly higher rate of degeneration and fibrosis, presumably from the compromised blood supply in the divided muscle.

SMVs as aortic counterpulsators. Working in our laboratory, Mannion *et al.* showed that properly conditioned SMVs with a vascular delay were able to function in the circulation effectively as diastolic counterpulsators (27, 28). The stroke work of these SMVs was 0.68×10^6 ergs after 4 hr, roughly three times the stroke work of the right ventricle and nearly half the left ventricular stroke work. Neilson, Chiu, and associated had also shown an improvement in the subendocardial viability ratio in SMVs of their own design (29).

Acker *et al.* (30) subsequently constructed SMVs in five mongrel dogs which differed from the design of previous chambers in that these had a cylindrical geometry with inflow and outflow on opposite ends of the chamber. These ventricles functioned chronically in the circulation as aortic diastolic counterpulsators

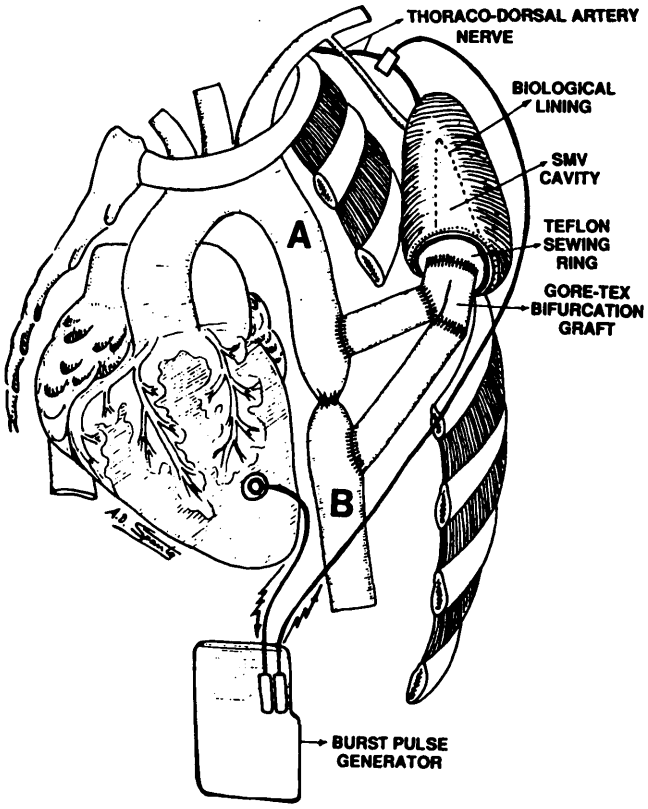

Figure 8. (original[2] Fig. 7) Diagram of SMV positioned as aortic diastolic counterpulsator. The SMV is on the outside of the chest wall. The limbs of the bifurcation graft have been divided, tailored, and rejoined to prevent kinking. Flow probes were placed around the aorta at Point A and B.

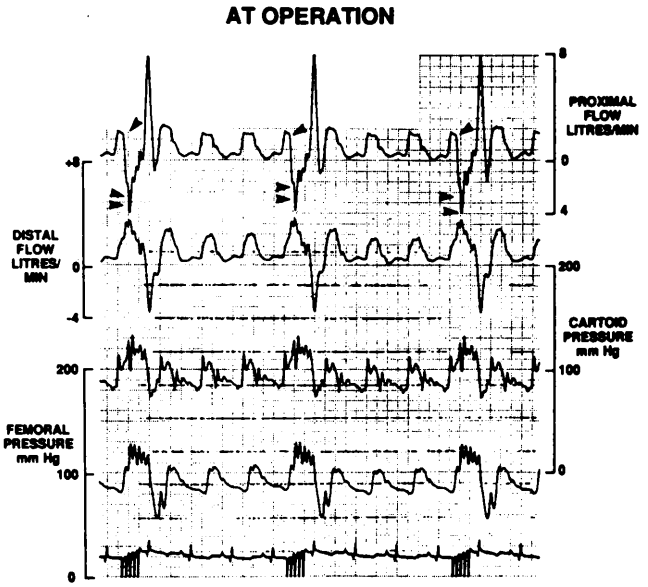

Figure 9. (original[2] Fig. 8) Recordings of ultrasonic flow and pressure taken at operation in one dog. Topmost trace is flow measured at Point A (Fig. 8) and demonstrates a sudden cutoff in the flow curve of the cardiac ejection (single arrowhead) when the SMV begins to contract and then reversal of blood flow towards the aortic arch (double arrowheads). Below that is flow at Point B (Fig. 8) showing increased distal aortic flow followed by passive reflux. Below, the carotid and femoral pressure traces show the increase in diastolic pressure as the SMV contracts. The burst of stimuli activating the thoracodorsal nerve can be seen on the ECG at the bottom.

for up to 11 weeks. All animals had functional SMVs at the time of death. These SMVs were capable of providing a substantial augmentation of forward blood flow with an increase of 29%, 40%, and 63% at 25, 43, and 85 Hz of thoracodorsal nerve stimulation, respectively. However, this study also demonstrated the thrombotic complications associated with these pumping chambers, despite the fact that they were lined with the relatively thromboresistant polytetrafluroethylene. The two longest surviving dogs, 5 and 11 weeks, were found to have multiple renal and splenic infarctions at autopsy. Neither animal, however, showed evidence of cerebrovascular or cardiac embolization.

Further studies have used the conically shaped SMV connected to the descending aorta by two Gore-tex grafts (W.L. Gore & Associates, Inc., Flagstaff, AZ). Figures 8 and 9 demonstrate this configuration with a corresponding ultrasonic flow and pressure recording taken in a single animal at the time of operation, while Figure 10 shows a pressure tracing in the same animal at one year of continuous stimulation. In these studies, ligation of the aorta by umbilical tape obligates the flow of blood through the SMV. The data from these experiments showed that SMVs were capable of proving long-term ventricular support, with the ability to augment diastolic pressure for up to 836 days (31). Of note, these chambers contained only the fibrous lining present after removal of the Teflon man-

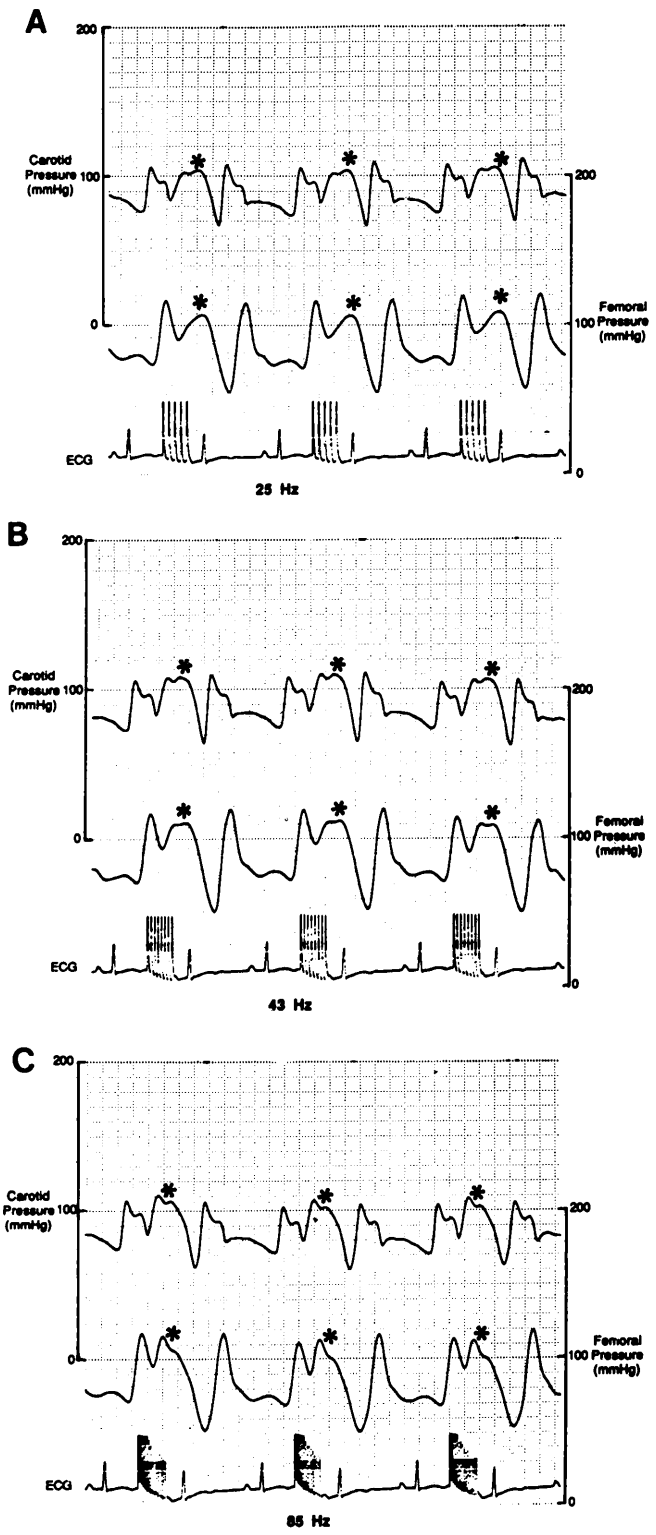

Figure 10. (original[2] Fig. 9) Arterial pressure and electrocardiogram traces taken at 1 year in the dog reported in Figure 9 whose SMV had been pumping continuously in the circulation for that length of time. Arterial pressures and electrocardiograms at pulse trains of 25, 43, and 85 Hz are shown in A, B, and C, respectively. Asterisks mark diastolic augmentation. The synchronization ratio is 1:2. The stimulator was set chronically at an R-wave delay of 175–250 msec, burst duration of 185–240 msec, 25-Hz burst, 2.5-V voltage, and 2:1 mode synchronization ratio (varying from 1:4, 1:3, or 1:2 depending on the native heart rate).

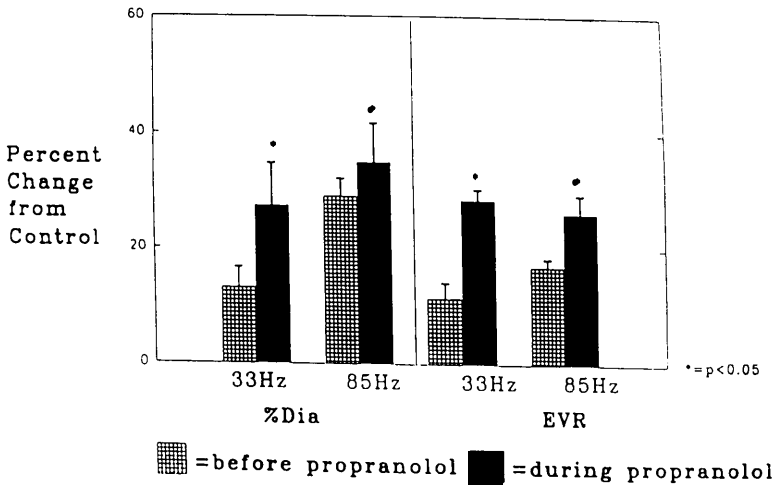

Figure 11. Bar graphs showing the percentile increases in diastolic augmentation (Dia) and the endocardial viability ratio (EVR) before and during propranolol infusion. Both diastolic augmentation and the endocardial viability ratio showed greater improvement under low cardiac output conditions.

drel and showed a dramatically lower incidence of thrombotic complications. Subsequent studies were performed using a propranolol-induced heart failure model (32). In these studies, the propranolol was used to decrease the mean arterial pressure by approximately 50%, and hemodynamic measurements were made with the animals under anesthesia. These investigators were able to show a greater increase in several hemodynamic parameters for the failing heart when compared with the normal heart. Mean diastolic pressure increased 27.6% vs 12.9%, and the endocardial viability ratio increased 28.7% vs 11.2%, respectively, as shown in Figure 11. Table I shows representative values at two different burst frequencies.

Additional studies have been performed in an effort to decrease the incidence of SMV thrombosis. Studies comparing the traditional SMV with autologously lined SMVs (with pleura or pericardium) have shown decreased thrombosis with the autologous lining (32, 33). In one of these series, 15 animals were reported on, showing no evidence of thromboembolism or SMV rupture at up to 589 days. This same group has studied the rate of rupture in the autologous-lined versus the fibrous-lined and found the pericardial lining substantially decreases the incidence of rupture (Thomas, unpublished). Therefore, in addition to providing protection against thromboembolism, the autologous lining also appears to improve the structural integrity of the chamber.

Most recently, a method has been developed in our laboratory for percutaneously seeding the SMV lumen with autologous endothelium. Preliminary studies have recently been reported and demonstrate that it is possible for SMVs to retain the endothelium after 3 hr of pumping blood in the circulation (34–36).

Conclusion

Skeletal muscle offers a realistic means of providing support for the failing myocardium. Clinical trials using cardiomyoplasty, where the muscle is wrapped directly around the failing heart, are currently underway. Preliminary reports have shown improvement in heart failure symptomatology as well as survival. Ad-

Table I. Hemodynamic Data before and during Propranolol Infusion

Variable	Before propranolol			During propranolol		
	Control	33 Hz	85 Hz	Control	33 Hz	85 Hz
Heart rate (bpm)	124 ± 10	129 ± 9	125 ± 10	102 ± 4[a]	103 ± 3	102 ± 4
CO (ml/min)	1042 ± 170	1082 ± 180[b]	1129 ± 187[b]	422 ± 61[a]	440 ± 60[b]	454 ± 58[b]
LV_{es} (mm Hg)	133.0 ± 3.1	111.1 ± 5.8[b]	113.7 ± 6.5[b]	77.5 ± 3.2[a]	73.6 ± 7.3	80.3 ± 7.7
LV_{ed} (mm Hg)	9.5 ± 1.9	9.0 ± 2.4	9.3 ± 2.3	15.4 ± 2.1[a]	14.3 ± 2.1	14.1 ± 2.3
Mean Ao_{dia} (mm Hg)	77.4 ± 5.8	87.4 ± 5.5[b]	100.0 ± 6.1[b]	45.6 ± 8.7[a]	58.2 ± 8.6[b]	61.6 ± 8.2[b]
Max + dp/dt (mm Hg/sec)	2308 ± 232	2419 ± 261	2414 ± 272	876 ± 220[a]	895 ± 209	977 ± 207
TTI (mm Hg/sec)	18.3 ± 1.0	18.2 ± 1.1	18.6 ± 1.1	14.9 ± 1.5[a]	14.8 ± 1.4	16.1 ± 1.3
DPTI (mm Hg/sec)	16.3 ± 2.0	18.0 ± 1.3[b]	19.3 ± 1.6[b]	13.0 ± 2.8[a]	16.6 ± 3.0[b]	18.2 ± 3.2[b]
EVR	0.89 ± 0.05	0.99 ± 0.03[b]	1.04 ± 0.03[b]	0.87 ± 0.06	1.12 ± 0.04[b]	1.10 ± 0.07[b]

Note. Data expressed as the mean ± SD. CO, cardiac output; DPTI, diastolic pressure-time index; EVR, endocardial viability ratio; LV_{ed}, left ventricular end-diastolic pressure; LV_{es}, left ventricular end-systolic pressure; max + dp/dt, maximum rate of change of left ventricular pressure; mean Ao_{dia}, mean aortic diastolic pressure; TTI, systolic tension-time index.

[a] $P < 0.05$ prepropranolol versus during propranolol.

[b] $P < 0.05$ versus control by repeated-measures analysis of variance.

ditional research is needed to elucidate the mechanism of this improvement.

Skeletal muscle ventricles have the potential to significantly augment left ventricular function and have pumped effectively in the circulation for 2½ years. With continued improvements in SMV design, including the improved results with autologous lining and the development of new models for systolic augmentation, the future for this mode of support is optimistic. Our laboratory is currently focusing on developing the LV apex-to-aorta system into a chronic model. Other investigators are continuing the development of dynamic aortomyoplasty. It seems apparent that as this exciting field continues to expand, so will the possibilities for eventual clinical application.

This article is an update of a previously published minireview entitled, "Skeletal muscle as a myocardial substitute" (Proc Soc Exp Biol Med **197**:109–118, 1991).

1. De Jesus FR. Breve consideraciones sobre un case de herida penetrante del corazon. Bol Assoc Med P R **23**:380–382, 1931.
2. Kantrowitz A, McKinnon W. The experimental use of the diaphragm as an auxillary myocardium. Surg Forum **9**:266–268, 1959.
3. Nakamura K, Glenn WWL. Graft of the diaphragm as a functioning substitute for the myocardium. J Surg Res **4**:435–439, 1964.
4. Sheppard MP. Diaphragmatic muscle and cardiac surgery. Ann R Coll Surg Engl **45**:212–231, 1969.
5. Salmons S, Vrobova G. The influence of activity on some contractile characteristics of mammalian fast and slow muscles. J Physiol **210**:535–549, 1969.
6. Mannion JD, Bitto T, Hammond R, Rubenstein N, Stephenson LW. Histochemical fatigue characteristics of conditioned canine latissimus dorsi muscle. Circ Res **58**:298–304, 1986.
7. Mannion JD, Hammond R, Stephenson LW. Canine latissimus dorsi hydraulic pouches: Potential for left ventricular assistance. J Thorac Cardiovasc Surg **91**:534–544, 1986.
8. Carpentier A, Chachques JC. Myocardial substitute with a stimulated skeletal muscle: First successful clinical case. (letter) Lancet **1**:1267, 1985.
9. Chachques JC, Grandjean P, Schwartz K, Mihaileanu S, Fardeau M, Swynghedauw B, Fontaliran F, Romero N, Wisnewsky C, Perier P, Chaucaud S, Bougeois I, Carpentier A. Effect of latissimus dorsi dynamic cardiomyoplasty on ventricular function. Circulation **78**(Suppl III):203–216, 1988.
10. Nakajima H, Niinami H, Hooper TL, et al. Cardiomyoplasty: Probable mechanism of effectiveness using the pressure-volume relationship. Ann Thorac Surg **57**:407–415, 1994.
11. Moreira LFP, Seferian P, Edimar A, et al. Survival improvement with dynamic cardiomyoplasty in patients with dilated cardiomyopathy. Circulation **82**(Suppl III):713, 1990.
12. Moreira LFP, Stolf NAG, Bocchi EA, et al. Clinical and left ventricular function outcomes up to five years after dynamic cardiomyoplasty. J Thorac Cardiovasc Surg **109**:353–363, 1995.
13. Armenti FR, Bitto T, Macoviak JA, Kelly AM, Chase CT, Hoffman BK, Rubenstein NA, St. John-Sutton M, Edmunds LH Jr, Stephenson LW. Transformation of skeletal muscle for cardiac replacement. Surg Forum **35**:258–260, 1984.
14. Bridges CR, Hammond RL, Dimeo F, Anderson WA, Stephenson LW. Functional right heart replacement with a skeletal muscle ventricle. Circulation **80**(Suppl III):1–9, 1989.
15. Niinami H, Hooper TL, Hammond RL, Ruggiero R, Lu H, Spanta AD, Pochettino A, Colson M, Stephenson LW. Skeletal muscle ventricles in the pulmonary circulation: Up to sixteen weeks experience. Ann Thorac Surg **53**:750–757, 1992.
16. Hooper TL, Niinami H, Lu H, Nakajima H, Ruggiero R, Nakajima HO, Stephenson LW. Skeletal muscle ventricles as left atrial-aortic pumps: Short-term studies. Ann Thorac Surg **54**: 316–322, 1992.
17. Lu H, Fietsam R Jr., Hammond RL, Nakajima H, Mocek FW, Thomas GA, Nakajima H, Colson M, Stephenson LW. Skeletal muscle ventricles, configuration left ventricular apex to aorta: acute in circulation studies. Ann Thorac Surg **55**:78–85, 1993.
18. Stevens L, Badylak SF, Janes W, Gray MH, Geddes LA, Voorhees WD III. Skeletal muscle ventricle made from rectus abdominis muscle in the dog. J Surg Res **46**:84–89, 1989.
19. Brister S, Fradet G, Dewar M, Wittnich C, Lough J, Chiu RCJ. Transforming skeletal muscle for myocardial assist: A feasibility study. Can J Surg **28**:341–344, 1985.
20. Sabiston DC Jr., Spencer FC. Assisted circulation. In: Elder D, Ed. Gibbon's Surgery of the Chest (4th ed). Philadelphia: W. B. Saunders, pp1502–1505, 1983.
21. Chachques JC, Grandjean PA, Fischer EC, et al. Dynamic aortomyoplasty to assist left ventricular failure. Ann Thorac Surg **49**:225–230, 1990.
22. Chachques JC, Haab F, Cron C, et al. Long-term effects of dynamic aortomyoplasty. Ann Thorac Surg **58**:128–134, 1994.
23. Hines GL, Mishinki Y, Williams L, Monroe K, Metwally N. Physiologic and pathologic evaluation of chronic extra-aortic counterpulsation with latissimus dorsi flap. J Cardiovasc Surg **382**:485–490, 1991.
24. Vertees RA, Cernaianu AC, Camishion RC, Cilley JH Jr., Baldino WA, DelRossi AJ. A surgical approach to chronic aortomyoplasty in the goat model. J Invest Surg **6**:419–429, 1993.
25. Lazarra RR, Trumble DR, Magovern J. Dynamic descending aortomyoplasty: Comparison with intraaortic balloon pump in a model of heart failure. Ann Thorac Surg **58**:366–371, 1994.
26. Cernaianu AC, Vassilidze TV, Flum DR, Gallucci JG, Olah A, Cilley JH Jr., Grosso MA, Del Rossi AJ. Lattisimus dorsi and serratus anterior dynamic descending aortomyoplasty for ischemic cardiac failure. Ann Thorac Surg **59**:639–643, 1995.
27. Mannion JD, Acker MA, Hammond RL, Stephenson LW. Four-hour circulatory assistance with canine skeletal muscle ventricles. Surg Forum **37**:211–213, 1986.
28. Mannion JD, Acker MA, Hammond RL, Faltemeyer W, Duckett S, Stephenson LW. Power output of skeletal muscle ventricles in circulation: short-term studies. Circulation **76**:155–162, 1987.
29. Neilson IR, Brister SJ, Khalafalla AS, Chiu RCJ. Left ventricular assistance in dogs using a skeletal muscle-powered device for diastolic augmentation. J Heart Transplant **4**:343–347, 1985.
30. Acker MA, Anderson WA, Hammond RL, Chin J, Buchanan JW, Morse CC, Kelly AM, Stephenson LW. Skeletal muscle ventricles in circulation: one to eleven weeks experience. J Thorac Cardiovasc Surg **94**:163–174, 1987.
31. Mocek FW, Anderson DR, Pochettino A, Hammond RL, Spanta A, Ruggiero R, Thomas GA, Lu H, Fietsam R, Nakajima H, Nakajima HO, Krakovsky A, Hooper T, Niinami H, Colson M, Levine S, Salmons S, Stephenson LW. Skeletal muscle ventricles in circulation long-term: 191 to 836 days. J Heart Lung Transplant **11**:s334–s340, 1992.
32. Thomas GA, Lu H, Isoda S, Hammond RL, Nakajima H, Nakajima HO, Colson M, Stephenson LW. Pericardium-lined skeletal muscle ventricles in the circulation up to 589 days. Ann Thorac Surg **58**:978–988, 1994.

33. Anderson DR, Pochettino A, Hammond RL, Hohenhaus E, Spanta AD, Bridges CR Jr., Lavine S, Colson M, Stephenson LW. Autogenously lined skeletal muscle ventricles in circulation: Up to nine months experience. J Thorac Cardiovasc Surg **101**:661–670, 1991.
34. Thomas GA, Lelkes PI, Chick DM, Isoda S, Lu H, Nakajima H, Hammond RL, Nakajima HO, Walters HL, Stephenson LW. Skeletal muscle ventricles seeded with autogenous endothelium. ASAIO J **41**:204–211, 1995.
35. Thomas GA, Lelkes PI, Chick DM, Lu H, Kowal TA, Hammond RL, Nakajima H, Nakajima HO, Spanta AD, Stephenson LW. Endothelial lined skeletal muscle ventricles: Open and percutaneous seeding techniques. J Cardiovasc Surg **10**:245–256, 1995.
36. Thomas GA, Lelkes PI, Isoda S, Chick D, Lu H, Hammond RL, Nakajima HO, Walters HL III, Stephenson LW. Endothelial-lined skeletal muscle ventricles in circulation. J Thorac Cardiovasc Surg **109**:66–73, 1995.