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A non-invasively determined surrogate of cardiac power ('circulatory power') at peak exercise is a powerful prognostic factor in chronic heart failure

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Objectives This study was designed to assess the prognostic value of a new variable derived from a cardiopulmonary exercise test, the circulatory power, a surrogate of cardiac power, at peak exercise, in patients with chronic heart failure.

Background Peak exercise cardiac power and stroke work are invasive parameters with recently proven prognostic value. It is unclear whether these variables have better prognostic value than peak oxygen uptake (VO_2).

Methods The study population comprised 175 patients with chronic heart failure (ejection fraction <45%) who underwent a cardiopulmonary exercise test. Circulatory power and circulatory stroke work were defined as the product of systolic arterial pressure and VO_2 and oxygen pulse, respectively. Prognostic value was assessed by survival curves (Kaplan–Meier method) and uni- and multivariate Cox analyses.

Results With a mean follow-up of 25 ± 10 months, ejection fraction, heart rate, systolic arterial pressure, peak VO_2, VCO_2, the anaerobic threshold, minute ventilation, the ventilatory equivalents of oxygen and carbon dioxide, the half times of VO_2 and VCO_2 recoveries, and the circulatory stroke work and power predicted outcome. Multivariate analysis demonstrated that the peak circulatory power (chi-square = 19·9, $P<0·001$) (but not peak circulatory stroke work) was the only variable predictive of prognosis.

Conclusion The prognostic value of cardiopulmonary exercise tests in heart failure patients can be improved by assessing a new variable, the circulatory power — a surrogate of cardiac power — at peak exercise.
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Key Words: Peak oxygen consumption, exercise, chronic heart failure, recovery, circulatory power, prognosis.

Introduction

The prognosis of patients with chronic heart failure is generally poor and various exercise-derived parameters have been proposed to predict it[1]. Among those parameters, peak oxygen uptake (peak VO_2) is the most predictive of outcome in a large number of studies[1–5]. However, this has been challenged recently. First, it has been suggested that peak VO_2 may lose its prognostic value in some groups of patients with very low or intermediate ranges of peak VO_2[6–8]. Second, studies using invasive haemodynamic measurements during exercise have shown that haemodynamic variables are of greater prognostic value than peak VO_2 in chronic heart failure patients: cardiac stroke work has thus emerged as the most powerful predictor of outcome in these groups of patients[9–11]. However, one may question the safety as well as the necessity of performing, as a routine, such invasive measurements, which are poorly compatible with a maximal level of exercise.

In our study, we hypothesized that using exercise test data, we could derive a cardiopulmonary index similar to stroke work that would have a similar prognostic value. The product of the oxygen pulse (the ratio oxygen uptake/heart rate) and systolic arterial pressure roughly equals the product of stroke work and the arteriovenous oxygen (AVO_2) difference. This equation associates a peripheral component to the central one of cardiac stroke work, labelling it 'the circulatory stroke work'. Similarly, the product of oxygen uptake and arterial pressure can be defined as 'the circulatory power'. Our hypothesis was that the changes in circulatory stroke

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work and power closely parallel those of cardiac stroke work and power, respectively, and the additional information about the blood pressure response further increases the prognostic value of peak VO_2.

The aim of this study was to assess the prognostic value of peak circulatory stroke work and power during exercise in patients with chronic heart failure.

Methods

Patients

One hundred and seventy five patients (19 women, 156 men) with stable chronic heart failure secondary to left ventricular systolic dysfunction, with a mean age of 53 ± 10 years, were included in the study between 1 January 1996 and 31 December 1998. The patients were in NYHA functional classes II (n=77), III (n=83) or IV (n=15) and all had a left ventricular ejection fraction less than 45% (mean 26 ± 10%) (as determined by radionuclide ventriculography or contrast angiography), except for 22 individuals in whom it was not determined, mainly because of atrial fibrillation (n=20); all those patients had an echocardiographic left ventricular end-diastolic diameter of more than 60 mm and a fractional shortening of less than 20%. The aetiology of heart failure was ischaemic in 32 cases and non-ischaemic (mainly primary cardiomyopathy) in the rest of the cases. Most of the studied patients were treated with angiotensin-converting enzyme inhibitors (95%) and diuretics (82%). Digoxin (32%), nitrates (28%), amiodarone (28%) and beta-blockers (12%) were less commonly used.

All the patients gave their informed consent and the protocol was approved by the local ethics committee.

Cardiopulmonary exercise tests

All tests were based on the classical methods and conducted in the upright position[12]. All patients performed an upright graded bicycle exercise with a workload increment of 10 watts per minute after an initial workload of 20 watts. Most of the patients were familiar with the procedure and were regularly encouraged to exercise until maximal exhaustion. The respiratory exchange ratio was always greater than one at the peak of exercise.

Respiratory gas analysis was carried out with a CPX-D Medical Graphics Corporation system (St Paul, Minnesota, U.S.A.). The system was calibrated with a standard gas mixture of known concentrations before each test. In order to stabilize resting gas measurements, subjects were asked to remain still on the bicycle for 3 min before exercising. A standard 12-lead ECG was continuously recorded. Heart rate was followed at each minute and blood pressure was measured by means of a mercury sphygmomanometer every 2 min and at the peak of the exercise. Because diastolic blood pressure can be difficult to measure with accuracy during exercise, even on a bicycle, its measurement was not taken into account in this study. Oxygen consumption (VO_2), carbon dioxide production (VCO_2) and the other common ventilatory parameters (minute ventilation (VE), breathing rate, etc.) were measured on a breath-by-breath basis. The results were averaged using a moving-average filter every seven breaths, excluding at each breath the highest and lowest values in order to reduce breath-by-breath noise. They were then averaged every 15 s and printed. Peak oxygen consumption was defined as the highest oxygen consumption obtained at the end of the test, and was expressed both in $ml \cdot min^{-1}$ and in $ml \cdot min^{-1} \cdot kg^{-1}$. The percent of predicted peak oxygen consumption (%) was calculated as peak oxygen consumption divided by maximal predicted oxygen consumption, using the values reported by Wasserman *et al.*[13] (%VO_2max). The ventilatory threshold was determined in 136 patients by classical methods[14,15].

The oxygen pulse (the product of stroke volume and AVO_2 difference) was calculated as the ratio VO_2/heart rate.

The level of ventilation was also assessed by the ventilatory equivalent of oxygen (VE/VO_2) and its efficiency by the ventilatory equivalent of carbon dioxide (VE/VCO_2).

At peak exercise, patients were asked to stop pedalling and measurements were continued for 5 min. The half time of recovery of VO_2 was determined as previously reported, as the time needed for VO_2 to decrease by 50% from its peak value[12]. The half-time of recovery of VO_2 could not be determined in 11 patients because of insufficient duration of recording; in two patients with severely depressed peak VO_2, the half-time recovery of VO_2 was apparently greater than 300 s, which suggested a non single exponential fitting. The half-time of recovery of VCO_2 was assessed in the same way. We also assessed the kinetics of recovery of heart rate by calculating the decrease in heart rate from peak exercise until the end of the first minute of recovery, divided by maximal predicted heart rate.

Circulatory power was calculated as the product of VO_2 and systolic arterial pressure using, for peak circulatory power, the peak VO_2 and the last systolic arterial pressure measurement (see Appendix). When systolic arterial pressure measurement was not obtained at peak exercise, we considered the value measured at the previous stage; if the last available measurement occurred more than 2 min before peak exercise, the systolic arterial pressure and the circulatory power were not considered (n=20 patients). Circulatory stroke work was calculated as the ratio of circulatory power by heart rate.

The rest, peak exercise and change (Δ) from rest to peak exercise of the various variables was considered.

Follow-up

The outcome was assessed either directly (when the patient's physician was a member of the medical staff),

or by contacting the patient's practitioner. The date and cause of death were documented in all cases. No patient was lost to follow-up. The mean follow-up was 25 ± 10 month. The event rate was high: 28 patients (16%) died (all of cardiac cause) and 32 others (18%) underwent cardiac transplantation. Since there is no consensus about the best way to consider heart transplantation in survival analyses, we used, as previously[5,16], two methods of analysis. First, we considered both death and transplantation as end-points (60 events) and second, we censored at the time of intervention patients who underwent cardiac transplantation (considering them alive at this time) (28 events).

Statistical analysis

Numerical values are presented as means ± standard deviation (SD). Differences between group means were tested by ANOVA, followed by Fisher's F test. The chi-square test was used to compare categorical variables. Linear regression analysis was based on the least-square method. *P* values of 0·05 or less were considered to denote statistically significant differences. All analyses were done with the Stat View 4.02 program (Abacus Concept, California, U.S.A.) for MacIntosh.

Prognostic value was determined by a Cox proportional hazards method for the following variables, considered as continuous variables: age, ejection fraction, the ventilatory threshold, peak VO_2, peak VO_2/kg, the percentage of predicted peak VO_2, rest and peak VE/VO_2 and VE/VCO_2, rest, peak and Δ heart rate, rest, peak and Δ systolic arterial pressure, the peak circulatory power, the peak circulatory stroke work as well as the half times of VO_2, VCO_2 and heart recoveries[17]. Aetiology and the NYHA class were entered as categorical variables. The exercise-derived variables predictive of survival by univariate analysis ($P<0·05$) were then entered in a Cox proportional hazards regression model (forward procedure) to determine their significance as independent predictors of outcome in multivariate analysis. When a variable was assessed by its resting, peak or Δ value, we only entered in the model the variable with the greatest chi-square value at univariate analysis to avoid colinearity problems. The anaerobic threshold was not entered in the model because of the missing values.

Kaplan–Meier cumulative mortality curves were plotted to the end of the follow-up period to describe trends in mortality over time in each of the risk categories[18]. Survival curves were compared by using the log-rank test (medians used as cut-off values).

Results

Exercise variables

Heart rate increased from 86 ± 18 to 145 ± 26 min^{-1} and systolic arterial pressure from 118 ± 23 to 155 ± 33 mmHg from baseline to peak exercise, respectively for the overall population.

The peak VO_2 was 20·3 ± 5·6 ml . min^{-1} . kg^{-1}, corresponding to 69 ± 19% of the predicted values. The anaerobic threshold was 13·0 ± 3·5 ml . min^{-1} . kg^{-1}. The half-time of recovery of VO_2 was prolonged to 107 ± 66 s.

Peak exercise circulatory stroke work was 1697 ± 70 mmHg . ml O_2^{-1}. Peak circulatory power was 243 907 ± 107 312 mmHg . ml O_2. min^{-1} or 3198 ± 1269 mmHg . ml O_2. min^{-1}. kg^{-2}.

Exercise variables and outcome

The aetiologies of chronic heart failure and the left ventricular ejection fraction were similar in the three groups of patients, those who died, those who survived and those who underwent cardiac transplantation. Patients who died or underwent transplantation had a poorer functional class, a lower exercise capacity, less increase in heart rate and arterial pressure and a longer time to recovery of VO_2 and VCO_2 (Table 1 and Fig. 1). VE/VO_2 and VE/VCO_2 were also increased at peak exercise in the patients with unfavourable outcome. Peak ventilation did not differ among the groups. Peak circulatory stroke work and power were greater in survivors than in the others. There were no differences between patients who died or were transplanted, except, as expected, for age, which was less important in those who had received transplants.

When both deaths and transplantations were taken into account, the following factors were significant determinants of adverse prognosis on univariate analysis: ejection fraction, heart rate (rest, peak, Δ), systolic arterial pressure (rest, peak, Δ), peak VO_2 whatever the mode of indexation, VCO_2, the anaerobic threshold, VE, VE/VO_2, VE/VCO_2, the half times of VO_2 and VCO_2 recoveries, the circulatory stroke work and power (Table 2). The Kaplan–Meier event-free survival curves built on the basis of the half-time of recovery of VO_2 and the circulatory power are shown in Figs 2 and 3 (both chi-square=9, $P=0·003$). When survival was analysed in terms of quartiles of peak VO_2 (Fig. 4) or circulatory power (Fig. 5), it appeared that prognosis was worse as peak VO_2 declined but that the circulatory power aids in selecting subgroups with particularly poor prognosis, those with both reduced peak VO_2 and reduced blood pressure.

The results obtained by multivariate analysis showed that only the peak circulatory power remained predictive of outcome (chi-square=19·9, $P<0·001$), just before the half-time of recovery of VO_2 (chi-square=3·4, $P=0·06$). When peak VO_2 was forced to enter first in the model in order to assess the value of the different variables above peak VO_2, only peak systolic arterial pressure (chi-square=6·1, $P=0·01$) remained in the model.

When only deaths were considered, most parameters retained their prognostic value along with age (Table 2). On multivariate analysis, again, only the peak

Table 1 Exercise variables in patients who died, were transplanted or survived

	Death (n=28)	Transplantation (n=32)	Alive (n=115)	*P*
Age (years)	59 ± 8	51 ± 10	53 ± 11	$<10^{-4}$ dead vs others
Ejection fraction (%)	21·7 ± 2·7	21·9 ± 8·8	27·7 ± 9·6	ns
NYHA class II/III/IV	7/16/5	6/21/5	64/46/5	$P=2{\cdot}10^{-4}$ alive vs others
Aetiology: ischaemic/non-ischaemic	3/25	4/28	15/98	ns
Max work rate (watts)	94 ± 30	93 ± 33	120 ± 32	$<10^{-3}$ alive vs others
Heart rate rest	90 ± 19	90 ± 20	84 ± 17	ns
Heart rate peak (min^{-1})	136 ± 31	143 ± 27	148 ± 24	<0·05 death vs alive
Δ heart rate (min^{-1}	48 ± 22	53 ± 19	64 ± 23	<0·05 alive vs others
% max predicted heart rate (%)	85 ± 20	87 ± 26	91 ± 18	ns
SAP rest (mmHg)	117 ± 22	109 ± 18	120 ± 24	<0·05 alive vs transplanted
SAP max (mmHg)	145 ± 32	138 ± 23	162 ± 33	<0·05 alive vs others
Δ SAP (mmHg)	27 ± 24	29 ± 20	43 ± 24	<0·01 alive vs others
VO_2 peak ($ml \cdot min^{-1}$)	1282 ± 435	1283 ± 492	1654 ± 449	$<10^{-4}$ alive vs others
VO_2 peak ($ml \cdot min^{-1} \cdot kg^{-1}$)	17·3 ± 4·5	17·1 ± 5·1	21·9 ± 5·3	<0·01 alive vs others
VO_2 peak (% predicted)	62 ± 15	57 ± 18	74 ± 18	$<10^{-4}$ alive vs others
Ventilatory threshold ($ml\ O_2 \cdot min^{-1}$)	12·1 ± 3·7	11·7 ± 3·2	13·7 ± 3·4	<0·05 alive vs transplanted
O_2 pulse peak ($ml\ O_2 \cdot beat^{-1}$)	9·8 ± 3·6	9·2 ± 3·8	11·4 ± 3·2	<0·05 alive vs transplanted
VCO_2 peak ($ml \cdot min^{-1}$)	1378 ± 457	1341 ± 499	1782 ± 503	$<10^{-4}$ alive vs others
VE peak ($l \cdot min^{-1}$)	57 ± 20	59 ± 17	64 ± 17	ns
VE/VO_2 peak	0·046 ± 0·014	0·055 ± 0·018	0·039 ± 0·008	<0·001 alive vs others
VE/VCO_2 peak	0·043 ± 0·011	0·047 ± 0·015	0·037 ± 0·007	$<10^{-3}$ alive vs others
T 1/2 VO_2 (s)	128 ± 54	138 ± 67	89 ± 32	$<10^{-4}$ alive vs others
T 1/2 VCO_2 (s)	151 ± 57	153 ± 57	115 ± 44	$<10^{-4}$ alive vs others
HR decrease at recovery (% max predicted value)	11 ± 9	10 ± 6	14 ± 14	ns
SAP × peak VO_2 ($mmHg \cdot ml\ O_2^{-1}\ min^{-1}$)	197 826 ± 86 886	187 547 ± 85 077	270 774 ± 108 124	<0·001 alive vs others
Peak SAP × peak VO_2 ($mmHg \cdot ml\ O_2 \cdot min^{-1} \cdot kg^{-2}$)	2567 ± 984	2402 ± 843	3573 ± 1273	<0·001 alive vs others
Peak SAP × peak VO_2 (mmHg . % predicted)	9308 ± 4001	7745 ± 2520	12 170 ± 4425	<0·001 alive vs others
Peak SAP × peak oxygen pulse ($mmHg \cdot ml\ O_2$)	1466 ± 599	1338 ± 645	1854 ± 690	<0·001 alive vs others
Peak SAP × peak oxygen pulse . kg^{-1} ($mmHg \cdot ml\ O_2 \cdot kg^{-1}$)	19·2 ± 7·3	17·1 ± 6·7	24·5 ± 8·4	<0·005 alive vs others

NYHA=New York Heart Association; SAP=systolic arterial pressure; VO_2=oxygen uptake; VCO_2=carbon dioxide production; VE=minute ventilation; T 1/2=half-time of recovery; HR: heart rate.

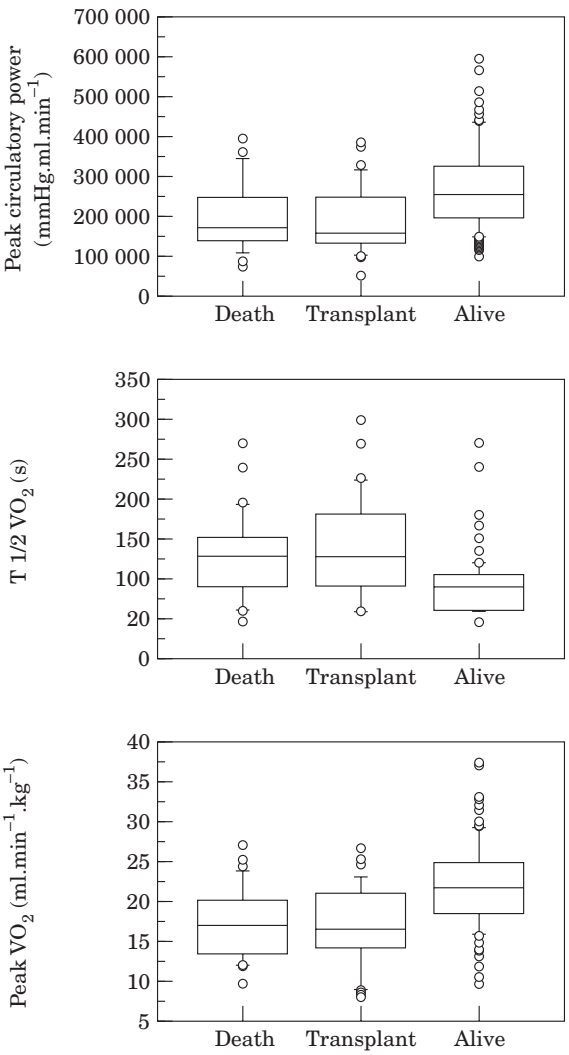

Figure 1 **Box-plots of the values of the peak circulatory power (top), the half-time of oxygen uptake recovery (T 1/2 VO_2, middle), and the peak VO_2 (bottom) in patients who died, underwent transplantation or survived. $P<0{\cdot}05$ for death or transplant vs alive for any variable.**

circulatory power independently predicted outcome (chi-square=10·0, $P=0{\cdot}001$). When peak VO_2 was forced to enter first in the model, no variable remained in the model.

Discussion

In recent years, the prognostic value of peak VO_2 in chronic heart failure patients has been challenged by new exercise-derived variables as well as by the invasive measurements, which showed significant prognostic insights beyond that provided by peak VO_2.

In our study conducted in a large series of 175 patients with chronic heart failure and low ejection fraction, we found, by means of univariate analysis, that various new cardiopulmonary exercise-derived parameters were predictive of prognosis besides peak VO_2. The results of the multivariate analysis confirmed that peak circulatory power, an index we introduced for the first time in the literature, was the best predictor of outcome in chronic heart failure patients. When peak VO_2 was forced to enter the model, peak exercise systolic arterial pressure remained the only variable independently predictive of outcome by multivariate analysis, confirming our hypothesis that the combination of VO_2 and the blood pressure responses strenghtens the prognostic value of the cardiopulmonary exercise test, especially in the subgroup of patients with low peak VO_2 and blood pressure at peak exercise.

Cardiac power, the product of cardiac ouput and mean arterial presure, is a potent index of cardiac systolic function[19]. Cardiac power was used many years ago by Tan *et al*. to predict prognosis[20] and also during exercise to assess cardiac pumping capability in heart failure[21]. The same group recently suggested that it was possible to assess the cardiac power output during exercise non-invasively by using the CO_2 rebreathing method to measure cardiac output during exercise[22]. The non-invasive measurement of cardiac power by echocardiography or radionuclide ventriculography during exercise or inotropic stimulation has shown some prognostic value[23,24].

The circulatory power can be assessed non-invasively during exercise conducted at its maximum. It is given by the triple product of cardiac output by systolic arterial pressure by AVO_2 difference. It can thus be assumed to mirror the cardiac power at peak exercise; this is true only if AVO_2 difference did not differ much at peak exercise among patients, and systolic and mean arterial pressure increase in parallel during exercise. Regarding AVO_2 difference, although this is not really the case as some patients can have reduced arterial oxygen content, especially when they are cachectic, or extract less oxygen at peak exercise, it has been shown that AVO_2 difference varies far less than cardiac output at peak exercise among patients with heart failure[25–27]. Second, although systolic and mean arterial pressure may not vary in parallel during exercise in heart failure patients, both are often used indifferently during exercise tests. Therefore, the circulatory power should not be viewed, in our opinion, as a perfect surrogate of cardiac power, but as an new global index that incorporates, besides AVO_2 difference, the heart rate, stroke volume, and blood pressure responses, all parameters whose prognostic value has been demonstrated (it is also plausible that a reduced AVO_2 difference response, because of high resting value, is associated with a poor haemodynamic reserve and perhaps a worse outcome). In addition, unlike the cardiac power measured by right heart catheterization, it can be measured at maximal and not only at submaximal exercise.

Exercise stroke work was determined as the most powerful of all the studied markers in the invasive studies[9–11,28]. In our study, peak exercise circulatory stroke work was of lesser prognostic value than peak exercise circulatory power. This is not surprising because

Table 2 Univariate predictors of poor outcome (death or death and transplantation) (abbreviations as in Table 1)

	Death or transplantation		Death only	
	Chi-square	*P*	Chi-square	*P*
Age (year)	0·4	0·55	6·8	0·009
Aetiology (men/women)	2·2	0·14	1·6	0·21
Ejection fraction (%)	11·3	0·0007	6·7	0·009
Work rate peak (w)	25·7	<0·0001	12·2	0·0005
Heart rate rest (min^{-1})	4·3	0·04	2·4	0·12
Heart rate peak (min^{-1})	4·9	0·03	4·4	0·036
Δ HR (min^{-1})	13·5	0·0002	8·8	0·003
SAP rest (mmHg)	3·8	0·05	0·5	0·45
SAP peak (mmHg)	12·9	0·0003	4·6	0·03
VO_2 peak ($ml \cdot min^{-1}$)	25·1	<0·0001	13·2	0·0003
VO_2 peak ($ml \cdot min^{-1} \cdot kg^{-1}$)	32·3	<0·0001	15·2	<0·0001
VO_2 peak (% predicted)	29·0	<0·0001	8·2	0·004
Ventilatory threshold ($ml \cdot min^{-1}$)	11·9	0·0005	3·2	0·07
O_2 pulse peak (ml)	11·7	0·0006	3·3	0·06
VCO_2 peak ($ml \cdot min^{-1}$)	26·4	<0·0001	12·1	0·0005
VE peak ($l \cdot min^{-1}$)	5·0	0·025	4·2	0·04
VE/VO_2 peak	21·3	<0·0001	4·6	0·03
VE/VCO_2 peak	28·6	<0·0001	5·8	0·01
T 1/2 VO_2 (s)	25·2	<0·0001	9·7	0·002
T 1/2 VCO_2 (s)	17·1	<0·0001	8·7	0·003
Δ SAP (mmHg)	12·8	0·0004	7·3	0·006
SAP × VO_2 peak ($mmHg \times ml \cdot min^{-1}$)	18·3	<0·0001	8·1	0·004
SAP × VO_2 peak (mm Hg × % predicted)	24·3	<0·0001	6·6	0·01
SAP × VO_2 peak ($mmHg \times ml \cdot min^{-1} \cdot kg^{-1}$)	26·3	<0·0001	10·7	0·001
peak SAP × peak oxygen pulse (mmHg × ml)	14·2	<0·0001	5·5	0·02
Peak SAP × peak oxygen pulse . kg^{-1} ($mmHg \times ml \cdot kg^{-1}$)	19·0	<0·0001	6·3	0·01
NYHA class	15·6	0·0004	6·1	0·05

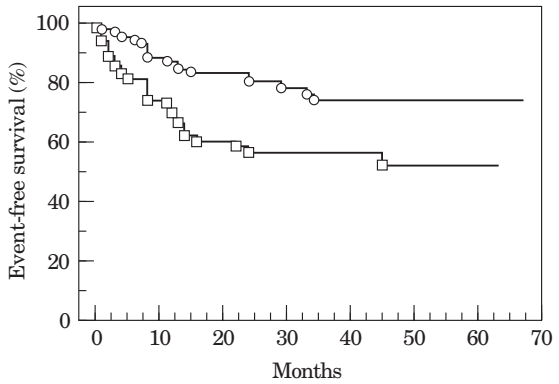

Figure 2 **Event-free survival curves according to T 1/2 VO_2, greater (□) or less (○) than the median value, 90 s (log rank: chi-square=9, P=0·003).**

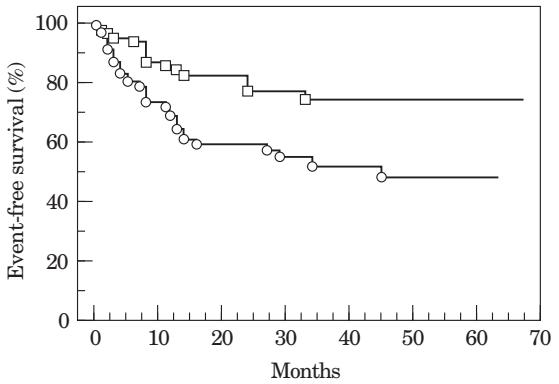

Figure 3 **Event-free survival curves according to peak exercise circulatory power, greater (□) or less (○) than the median value, 3·047 $mmHg \cdot ml.min^{-1} \cdot kg^{-2}$ (log rank: chi-square=9, P=0·003).**

circulatory stroke work equals the oxygen pulse times the arterial pressure; we have shown that the prognostic value of peak exercise oxygen pulse was less than that of peak VO_2 in heart failure patients[5], probably because the VO_2 response integrates the heart rate response, the prognostic value of which has been recently confirmed[29]. Similarly, the circulatory power integrates the chronotropic response. Therefore, we support the use of circulatory power in these patients. Whether this variable has greater prognostic value than the cardiac power measured during exercise by right heart catheterization remains to be further evaluated. However, one may question the reality of a 'maximal' exercise test performed with invasive measurements as well as the safety of performing invasive tests in these groups of frail patients.

The kinetics of recovery of VO_2 is another new marker, close to the peak circulatory power that emerged in our analysis. Oxygen consumption recovery is prolonged in heart failure[12,30–32]. We have previously shown that the half-time of recovery of VO_2 was largely

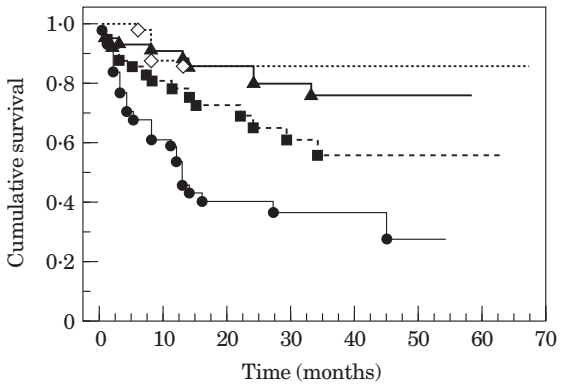

Figure 4 **Event-free survival curves according to quartiles of peak VO_2 (% of predicted values) (log rank: chi-square=33, $P<0·0001$). ●=Lower quartile; ■=quartile 25–50%; ▲=quartile 50–75%; ◇=upper quartile. Logrank chi-square=33, $P<0·0001$.**

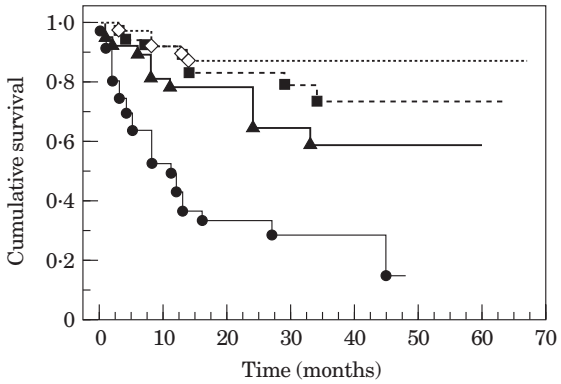

Figure 5 **Event-free survival curves according to quartile of peak exercise circulatory power (log rank: chi-square=46, $P<0·0001$). ●=Lower quartile; ■=quartile 25–50%; ▲=quartile 50–75%; ◇=upper quartile. Logrank chi-square=46, $P<0·0001$.**

independent of the level of exercise, at least as long as it remains greater that 75% of the maximum[12]. This can be particularly interesting in chronic heart failure patients who, as a result of fear or poor motivation, and in whom peak VO_2 is often underestimated, often stop exercising before maximum symptoms. Whether this parameter is more dependent on cardiac or peripheral factors is a matter of debate[33]. De Groote *et al.*[34], whose assessment was different from ours, found that the kinetics of recovery of VO_2, was an independent predictor of outcome in patients with a less reduced peak VO_2. We extend these observations by showing that the half-time of recovery of VO_2 (but not the half-time of recovery of VCO_2) has a highly powerful prognostic value even in patients with severe heart failure. The kinetics of heart rate recovery was found to have no prognostic value in this population of patients with heart failure.

Recent studies have also found that markers of ventilatory efficiency such as peak VE/VCO_2 or the slope of VE/VCO_2 relationship are of prognostic value[29,35,36]. We did not measure the latter in the present study; the former, although predictive of outcome, did not appear to be superior to peak circulatory power or peak VO_2.

Limitation

A large number of our patients underwent cardiac transplantation. As peak VO_2 is now widely used to determine the time of transplantation, we therefore conducted another model of analysis considering only death as outcome, despite the fact that this analysis may severely bias the results of our population where transplantation was largely performed: this yielded similar results and peak circulatory power remained the best and only predictor of death by multivariate analysis.

We have neglected LV end-diastolic pressure in the formula of the circulatory stroke work or power, although it is not negligible in heart failure, especially during exercise.

The accuracy of blood pressure measurement at peak exercise may not be perfect. Cuff arterial pressure is not aortic pressure and given the increased arterial stiffness and amplification of systolic pressure from the aorta to the periphery with age, the value of the circulatory power in very old patients needs more evaluation.

Conclusions

The product of peak VO_2 by peak systolic arterial pressure (the circulatory power), a surrogate of peak exercise cardiac power, an invasive parameter which has shown greater prognostic value than peak VO_2 in patients with chronic heart failure, but is difficult to measure at a maximal level of exercise, has a high prognostic value. Peak exercise circulatory stroke work, a surrogate of peak stroke work, has less prognostic value. Our results highlight the prognostic value of the blood response beyond peak VO_2: patients with a low circulatory power have a particularly poor prognosis. Finally, the half-time of recovery of VO_2 appears as another powerful prognostic parameter, very simple to determine.

This study was presented at the American College of Cardiology meeting, in Anaheim, in March 2000.

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Appendix

(1) Calculation of circulatory stroke work

Stroke work = stroke volume × (LV systolic arterial pressure − LV end-diastolic pressure).

Stroke work × arteriovenous oxygen difference = stroke volume × (LV systolic arterial pressure − LV end-diastolic pressure) × arteriovenous oxygen difference.

If LV end-diastolic pressure is neglected:

Stroke work × arteriovenous oxygen difference = stroke volume × LV systolic arterial pressure × arteriovenous oxygen difference = stroke volume × arteriovenous oxygen difference × arterial systolic pressure.

Thus:

Stroke work × arteriovenous oxygen difference = oxygen pulse × arterial systolic pressure.

(2) Calculation of circulatory power

Cardiac power = cardiac output × mean arterial pressure

If systolic arterial pressure is used in place of mean arterial pressure:

Cardiac power = cardiac output × systolic arterial pressure

Thus:

Cardiac power × arteriovenous oxygen difference = cardiac output × systolic arterial pressure × arteriovenous oxygen difference = VO_2 × systolic arterial pressure