

A comparison of voluntary and electrically induced contractions by interleaved ^1H - and ^{31}P -NMRS in humans

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Vanderthommen, M., S. Duteil, C. Wary, J. S. Raynaud, A. Leroy-Willig, J. M. Crielaard, and P. G. Carlier. A comparison of voluntary and electrically induced contractions by interleaved ^1H - and ^{31}P -NMRS in humans. *J Appl Physiol* 94: 1012–1024, 2003. First published November 27, 2002; 10.1152/jappphysiol.00887.2001.—Skeletal muscle voluntary contractions (VC) and electrical stimulations (ES) were compared in eight healthy men. High-energy phosphates and myoglobin oxygenation were simultaneously monitored in the quadriceps by interleaved ^1H - and ^{31}P -NMR spectroscopy. For the VC protocol, subjects performed five or six bouts of 5 min with a workload increment of 10% of maximal voluntary torque (MVT) at each step. The ES protocol consisted of a 13-min exercise with a load corresponding to 10% MVT. For both protocols, exercise consisted of 6-s isometric contractions and 6-s rest cycles. For an identical mechanical level (10% MVT), ES induced larger changes than VC in the P_i -to-phosphocreatine ratio [1.38 ± 1.14 (ES) vs. 0.13 ± 0.04 (VC)], pH [6.69 ± 0.11 (ES) vs. 7.04 ± 0.07 (VC)] and myoglobin desaturation [43 ± 15.9 (ES) vs. $6.1 \pm 4.6\%$ (VC)]. ES activated the muscle facing the NMR coil to a greater extent than did VCs when evaluated under identical technical conditions. This metabolic pattern can be interpreted in terms of specific temporal and spatial muscle cell recruitment. Furthermore, at identical levels of energy charge, the muscle was more acidotic and cytoplasm appeared more oxygenated during ES than during VC. These results are in accordance with a preferential recruitment of type II fibers and a relative muscle hyperperfusion during ES.

muscle metabolism; electrical stimulation; high-energy phosphates; myoglobin oxygenation; human; nuclear magnetic resonance spectroscopy

NEUROMUSCULAR ELECTRICAL STIMULATIONS (ES) are frequently used to strengthen normal muscle (24). In pathology, several investigators have shown the merit of ES for the treatment of amyotrophy related to immobilization (12). The efficacy of ES of the quadriceps during rehabilitation after anterior cruciate ligament surgery has been well documented (8, 10). Percutaneous electrodes facing muscle motor points are used to stimulate muscle in stimulation/rest cycles. The stimulation frequency, typically 50 to 100 Hz, is chosen to induce tetanic contractions. Sensory discomfort related

to current intensity varies considerably between subjects but remains the major limitation to strength improvement (24). Eriksson and Häggmark (12) concluded that, in the context of rehabilitation, the addition of neuromuscular ES to voluntary exercise was superior to isometric voluntary contractions (VC) alone. To explain this advantage of combining ES with VC, it was hypothesized that electrically induced contractions imposed a specific recruitment pattern depending on location of depolarized motor units within the muscle (23) and also increased the metabolic demand for ES compared with VC for a given force development (49).

Different techniques have been used to study the metabolism of electrically contracted muscle in humans. In the 1980s, biopsy samples were taken from the electrostimulated quadriceps (43, 44), but this invasive technique does not allow dynamic investigations in the same tissue sample. Myoelectric signal detection (23) demonstrated a modification in the order of motor unit recruitment, and the electromyogram root-mean square (34) technique showed a pronounced, low-frequency fatigue during electrically elicited contractions.

An improved understanding of the mechanisms involved during neuromuscular ES could be gained from newly available interleaved NMR techniques (5, 41). These can acquire several biochemical and physiological parameters noninvasively during exercise. In vivo NMR spectroscopy (NMRS) of ^{31}P can continuously monitor the phosphorylated metabolites involved as energy transducers (2, 21). First reported in 1981 with investigations of healthy (7) and diseased (40) human skeletal muscles, ^{31}P -NMR has become the most popular nucleus in exploring muscle metabolism. In vivo ^1H -NMRS of deoxymyoglobin in exercising human muscle was pioneered by Wang et al. (51) and gives instant information on the oxygenation state of muscle cells. Simultaneous ^{31}P - and ^1H -NMRS of human skeletal muscle, first realized by Richardson et al. (39), can collect both these parameters during the same physiological event, providing an invaluable tool for the in vivo study of tissue metabolism.

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Compared with VC, NMR investigations of neuromuscular ES present additional technical difficulties but have nonetheless been carried out in healthy (1, 25, 28, 50) and paraplegic subjects (14). Here, we present the first exploration of muscle metabolism in humans during tetanic, intermittent ES by interleaved multinuclear NMRS. An electronic link was constructed to filter and synchronize tetanic intermittent ES of the quadriceps with NMR acquisitions in a large bore magnet, and an NMR sequence was implemented to interleave ^1H - and ^{31}P -spectroscopy signals acquired with a double-tuned surface coil.

The purposes of the present work were 1) to monitor high-energy phosphate metabolism and cellular oxygenation in the electrostimulated quadriceps, simultaneously, with an adequate temporal resolution; 2) to compare these with the same parameters evaluated during a protocol of VC in the same subjects; and 3) from the detailed analysis of these parameters, to gain a better understanding of the specific metabolic patterns involved during neuromuscular ES. The specific objectives were to determine whether 1) the energy demand during ES was higher than during VC and whether this difference persisted when taking into account the differences in mass of quadriceps involved in the two procedures; 2) glycolytic fibers were preferentially recruited during ES, compared with VC, as would be indicated by a faster decline of intracellular pH with increasing levels of ADP; 3) the intracellular P_{O_2} drop was a mechanism to increase O_2 flux in response to the higher energy demand during ES; 4) the fall in intracellular P_{O_2} during ES might be modulated by factors other than the high-energy demand, in particular by the hyperperfusion that has been revealed by previous PET studies (48).

MATERIAL AND METHODS

Eight healthy male volunteers (age 22.5 ± 2.9 yr) who had given informed, written consent were studied. All subjects were involved in recreational physical activities. The protocol was authorized by the ethics committees of the University of Liège (Belgium) and the Kremlin Bicêtre University Hospital (France). Subjects first underwent an evaluation to determine the quadriceps maximum isometric voluntary torque (QMIVT) from the left lower limb. One week later, metabolism was investigated in the left quadriceps with NMRS during a VC session on 1 day and an ES session on the following day. After the stimulated exercise, the maximal myoglobin (Mb) desaturation was measured during an ischemia of the thigh. To verify the absence of cumulative effects on metabolism of either VC or ES, two subjects performed a second VC session after the ES and ischemia sessions.

QMIVT Measurement

The isometric torque of the quadriceps was measured on a dynamometer via a static strain-gauge transducer (DS Europe, FS 100 kg). The subject was placed in a knee extensor testing chair with 60° of knee flexion and 30° of hip flexion and was asked to exert three maximum isometric knee extensions for 4 s with 2-min recoveries between contractions. The highest torque measured was recorded as the QMIVT value (246 ± 49 N·m). The gravity torque of the left leg was

also measured (13 ± 2 N·m) and was taken into account in the QMIVT measurement.

VC Protocol

Subject position and material. For the VC protocol, the subject was positioned supine in the magnet (Fig. 1). The left thigh was set on an adjustable inclined plane that imposed 30° hip and 60° knee flexion. The subject wore a therapy boot attached with a nylon rope to weights outside the magnet via two pulleys. This custom-built ergometer was adjusted so that the rope was perpendicular to the leg axis. The load was imposed as percentage of QMIVT, calculating the weights with respect to the QMIVT as the gravity torque of the leg and the distance between the articular interline of the knee and the point where the rope was attached to the boot (0.42 ± 0.01 m).

Exercise characteristics. The subject performed a progressive exercise of the quadriceps composed of different steps. Bouts of 5-min exercise alternated with periods of 5-min rest. During exercise, the subject was instructed to raise his heel by 2 cm at an acoustic signal and to maintain it during 6 s until another signal. Resting and lifting alternated every 6 s for each 5-min bout. The workload was incremented by 10% of QMIVT at each step, starting at 10% of QMIVT (28 ± 8 N) and ending at exhaustion, which corresponded to 50% of QMIVT (259 ± 50 N) for five subjects and 60% of QMIVT (300 ± 43 N) for three others. An observer positioned near the distal aperture of the magnet monitored the exercise and informed the volunteer of how high he lifted his heel during contraction periods.

ES Protocol

Subject position and material. Subject position and materials used were the same as in the VC protocol (Fig. 1).

Exercise and ES characteristics. The subject performed one electrically elicited effort that lasted 13 min and was followed by a recovery of 7 min. The isometric contraction (6 s)/rest (6 s) cycles were applied with a workload corresponding to 10% of QMIVT. This protocol was chosen for its efficiency in improving quadriceps strength in able-bodied subjects (11) and because it avoids quadriceps atrophy during the rehabilitation period in patients with knee arthroscopy (47). The contraction period had a 0.75-s rise time, a 5-s plateau, and a 0.25-s fall time. The stimulator provided bidirectional symmetric rectangular impulses directly to the skin through elastomer surface electrodes. Pulse frequency and width were 50 Hz and 0.25 ms, respectively. One channel was used with one pole connected to a stimulating electrode (4.5×5 cm) and the other one to a dispersive electrode (9×5 cm). The stimulating electrode was placed on the motor point of

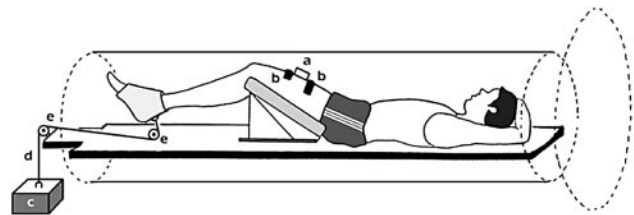


Fig. 1. Graphical scheme of experimental conditions during electrical stimulations (ES) and voluntary contractions (VC) in the 46-cm bore magnet. Surface coil (a) and electrodes (b) are positioned on the rectus femoris. ES or VC induce intermittent isometric contractions against a workload (c) positioned outside the magnet via a rope (d) and pulleys (e).

the left rectus femoris. The distance between the electrode's distal side and the patellar base ranged from 13 to 18 cm. The dispersive electrode was placed transversally on the proximal part of the quadriceps, with its lower edge 5 cm above the upper edge of the stimulating electrode. During each evoked contraction of ES, the current intensity required to raise and maintain the subjects heel by 2 cm was adjusted by an operator at the console, according to instructions given by the observer in the NMR room. The current intensity increased linearly ($R^2 = 0.98$) between the beginning (54 ± 12 mA) and the end (69 ± 15 mA) of stimulation.

Ischemia Protocol

For the ischemia protocol, the subject was positioned supine on the examination bed with legs extended and with an air cuff placed around the proximal part of the left thigh. The ischemic stress protocol consisted of 420-s leg ischemia induced by rapid inflation of the air cuff to 220 Torr. This provided a deoxyglobin reference signal corresponding to 100% desaturation (6).

NMR Measurements

Equipment. Experiments were carried out on a 4-T superconducting magnet (Magnex 4/60) interfaced to Bruker's Biospec NMR spectrometer and console. Magnet clear bore was 46 cm. A 5-cm diameter dual-tuned (¹H and ³¹P) surface coil was taped on the leg and faced the left rectus femoris. Identical positioning of the coil in the VC, ES, and ischemia protocols was ensured by measuring the distance between the distal point of the coil and the patellar base (extreme values: 18–23 cm) and by tracing ink marks on the subjects' skin. The surface coil was placed exactly between both electrodes for the ES protocol and distally from the air cuff for the ischemia protocol.

Despite difficult experimental conditions regarding centering inside the magnet, B₀ field homogeneity was efficiently adjusted by an automatic localized first- and second-order shim procedure, FASTMAP, implemented by Bruker. The line width at half height of the H₂O peak was systematically ≤ 40 Hz.

ES-NMR interfaces. ES pulses were filtered between the stimulator (outside the Faraday cage) and the electrodes (inside the magnet) to avoid picking up ES electronic noise by NMR. A 100-ms pulse was programmed into the NMR sequence to trigger both ES via an electronic short circuit relay and NMR acquisitions every 12 s.

³¹P measurement at rest. Before the VC and ES exercises, a ³¹P spectrum was acquired in 96 s [64 accumulations, repetition time (TR) = 1.5 s] to obtain baseline values of the high-energy phosphates.

Interleaved sequence. Interleaved ¹H- and ³¹P-NMRS acquisition modules were performed by using the Bruker multiscan control tool (35). Combined ¹H-³¹P data sets were acquired every 2 s throughout the entire VC and ES protocols.

¹H-module. The deoxyglobin resonance at 75 parts/million (ppm) downfield relative to water originates from the $n\text{-}\delta$ proton of the proximal histidine F8 of Mb in the deoxygenated state. This resonance was selectively excited by a 0.4-ms Gaussian pulse at a TR of 18 ms with 64 accumulations (512 complex points; acquisition time of 10 ms).

³¹P-module. High-energy phosphates were excited by a 0.25-ms single square pulse and acquired over 1,024 complex points (acquisition time of 255 ms).

Data processing. Interleaved raw data were automatically stored as separate ¹H and ³¹P spectroscopic components.

Data were then processed by using the standard manufacturer software (XWIN NMR) under which a number of automations were written for batch processing of the spectra. To improve the signal-to-noise (S/N) ratio, 6×64 free induction decays (FIDs) from the ¹H-module and 6×1 FID from the ³¹P-module were summed to lead to a time resolution of 12 s, corresponding to one contraction/rest cycle.

¹H-module. Manual phasing (*order 0* and *1*) and automatic fourth-order polynomial baseline corrections ($+20/-20$ ppm relative to the deoxyglobin peak) were applied after exponential multiplication (50 Hz) and Fourier transformation. Integration markers were manually selected for the deoxyglobin peak (approximately ± 3 ppm). The percentage of Mb desaturation was calculated by using the signal intensity after ischemia as the reference value of 100% desaturation. All deoxyglobin peak areas were normalized to this reference after taking the different number of accumulations into account (64×6 for VC or ES and 256 for ischemia). Conversion to PO₂ values was calculated from the O₂-binding curve for Mb {PO₂ = [(1 - x)/x]P₅₀}, where x is the fraction of Mb that is not oxygenated and P₅₀ is the Mb half-saturation pressure. A P₅₀ of 3.2 Torr was used (38).

³¹P-module. The ³¹P-FIDs were exponentially multiplied (8 Hz) before Fourier transformation, manual phasing of the reference spectrum, and automatic baseline correction. The P_i, phosphocreatine (PCr), and γ -, α -, and β -ATP peak limits were identified from frequencies referenced to the PCr peak. Peak picking and integration were automatically performed over the stack of spectra. The P_i chemical shift was taken as the center of gravity of the P_i resonance within 3.5–5.5 ppm limits. This procedure was applied to take into account possible deformation and asymmetry of the P_i peak during exercise. Intracellular pH changes were computed from the chemical shift (δ) of the P_i peak relative to PCr, according to the equation $\text{pH} = 6.75 + \log[(\delta - 3.27)/(5.69 - \delta)]$ (45). The free cytosolic ADP concentration ([ADP]) was calculated from the P_i/PCr ratio by using a reformulation of the creatine kinase reaction: $[\text{ADP}] = 8.2\text{P}_i/\text{PCr} \times 10^{(\text{pH}-6)}/1.66$. In this equation, [ATP] is taken as 8.2 mM, the creatine kinase equilibrium constant as $1.66 \times 10^9 \text{ M}^{-1}$ and creatine concentration is assumed to be equal to P_i concentration (20).

For the VC and ES protocols, data of PCr recovery were fitted by a monoexponential function to determine the PCr time constant of recovery (τ PCr). During the recovery period, the mean pH was calculated over a time period equal to the τ PCr measured. The pH was introduced into the formula that corrects for the dependence of PCr recovery on cytosolic pH (19).

The pH-[ADP] and the PO₂-[ADP] relationships were also studied during both exercises. For these two relationships, the experimental data were fitted with a monoexponential model.

Ischemia sequence. LEVEL OF Mb DESATURATION. Only ¹H spectroscopy was performed during this sequence, which was composed of number of repetitions (NR) = 67 blocks of the number of scans = 256 excitations of deoxyglobin by a 0.4-ms Gaussian pulse at a TR of 20 ms.

The sequence was started just after the inflation of the air cuff was achieved. ¹H-FIDs were processed identically to those from the ¹H module of the interleaved sequence, and the increase of deoxyglobin signal was fitted to a sigmoid model. The maximal point of this curve was taken to be the 100% desaturation reference value.

Mb QUANTIFICATION. At the end of the ischemia, additional acquisitions (NR = 4) were performed with a TR of 100 ms to obtain a factor of correction for the quantification of Mb. TR was chosen to be largely superior to the longitudinal relax-

ation time (T1) of Mb at 4 T (~10 ms). Moreover, a fully relaxed spectrum of muscle water was acquired to quantify Mb concentration ([Mb]) with reference to tissue water (6).

[Mb] relative to water was calculated from the respective peak areas (A), receiver gains (RG), number of scans (NS), number of hydrogens per resonance (N), and molar concentration of water (M_{H₂O})

$$[\text{Mb}] = \frac{A_{\text{Mb}}}{A_{\text{H}_2\text{O}}} \times \frac{\text{RG}_{\text{H}_2\text{O}}}{\text{RG}_{\text{Mb}}} \times \frac{\text{NS}_{\text{H}_2\text{O}}}{\text{NS}_{\text{Mb}}} \times \frac{N_{\text{H}_2\text{O}}}{N_{\text{Mb}}} \times M_{\text{H}_2\text{O}}$$

Statistical Analysis

Data are presented as means ± SD, except when stated otherwise. Statistical analysis of the successive steps in the VC protocol (PCr depletion, τ PCr, P_i/PCr, pH, Mb desaturation, and P_{O₂}) was performed by using repeated-measures ANOVA. To correct for the very asymmetric distribution of the P_i/PCr ratios, a log transformation was applied before the ANOVA analysis. When a significant difference was detected, a subsequent comparison of means was made according to the Bonferroni test (NCSS software). For P_i/PCr, pH, and Mb desaturation, we used the Bonferroni “with control” comparison test. The control value corresponded to measurements at rest.

Differences between ES and the different steps of the VC protocol in the evaluated parameters (PCr depletion, τ PCr, P_i/PCr, pH, Mb desaturation, and P_{O₂}) were assessed with repeated-measures ANOVA and the Bonferroni with control comparison test. The control value corresponded to the ES measurement.

A multiple-factor ANOVA was used to assess differences between pH measured during the last minute of each step and pH measured during the first minute of the following recovery, and differences between the steps and the interaction between these two parameters.

RESULTS

VC Protocol

The P_i/PCr ratio and deoxymyoglobin increased and intracellular pH dropped proportionally to the workload during the exercise bouts. They all returned toward baseline values during the successive recovery phases. For each individual subject, the construction of stacked plots of ³¹P- and ¹H-NMRS spectra gives a visual impression of the progression of the metabolic changes during the 10, 20, 30, 40, and 50% QMIVT steps and the interleaved recoveries. To improve clarity, only one spectrum out of five (1 spectrum/min) is shown in Fig. 2. For PCr, P_i/PCr, pH, and deoxymyoglobin, the mean curves were reconstructed from the actual individual data sets (Fig. 3).

Table 1 summarizes the mean ³¹P- and ¹H-NMRS results obtained at rest and at the end (last minute) of the different steps. PCr depletion increased statistically (*P* < 0.0001 between all steps, except *P* < 0.01 between 10 and 20%). The P_i/PCr ratio progressively increased from the resting value through the different steps. The differences were statistically significant between all steps (*P* values ranging from <0.05 to <0.0001). Compared with the resting value, end-stage pH was more acidic for the 30% (*P* < 0.01), 40%, 50%, and last QMIVT steps (*P* < 0.001). Between rest, 10, 20, and 30% QMIVT, Mb desaturation rose progres-

sively from -3.3, 6.1, and 22.3% to 37.6%, and the differences were statistically significant between each step (*P* < 0.05). Mb desaturations ranged from 37.6 to 43.1% for steps 30% and onward (*P* > 0.05). For the P_{O₂} level, as calculated from Mb desaturation, we measured a statistical difference between the 10% QMIVT step and all other steps (*P* < 0.01).

In the early phase of recovery after each step, intracellular pH continued to fall. Compared with the last minute of exercise, mean values of pH measured during the first minute of recovery were statistically lower, and this difference increased with the workload (*P* < 0.001).

For the last steps (from 30% of QMIVT to the last step), recoveries of PCr could be closely fitted to a monoexponential curve. The τ PCr was prolonged with increasing force level and reached the mean values of 40.9 ± 8.2, 51.9 ± 11.4, and 62.7 ± 17.4 s for the recovery of the 30, 40, and 50% QMIVT steps, respectively. After correction for pH (19), τ PCr was not found to be statistically different: 32.6 ± 5.8, 37.5 ± 10.7, and 42.8 ± 18.5 s for the 30, 40, and 50% QMIVT steps, respectively (*P* = 0.66).

The two subjects who performed a second VC after the ES protocol did not show statistically different results during the second VC from those measured during the first VC protocol for P_i/PCr, pH, and Mb desaturation: 1.04 ± 0.28 vs. 1.16 ± 0.28, *P* = 0.51; 6.95 ± 0.04 vs. 6.94 ± 0.04, *P* = 0.54; 43.9 ± 2.87 vs. 41.2 ± 2.97%, *P* = 0.28, respectively, during the last step.

ES Protocol

Typical stacked plots of ³¹P- and ¹H-NMRS spectra, obtained in the same subject as in Fig. 2, but during ES and recovery, are provided in Fig. 4. As for Fig. 2, only one spectrum in five is shown.

For PCr, P_i/PCr, pH, and deoxymyoglobin, the mean curves were reconstructed from the actual individual data sets (Fig. 5). From the comparison of the four curves, it is patent that parameters showed marked variations during the first 2 min of ES and reached extreme values around *minute* 3 of ES. Maximal PCr depletion of 53.7 ± 17.8% was noted after 258 s of ES; maximal mean P_i/PCr of 1.38 ± 1.14 was noted after 198 s of ES; a minimal mean pH value of 6.69 ± 0.11 was observed after 198 s of ES; and a maximal mean value of Mb desaturation of 43.0 ± 15.9% was noted after 66 s of ES. From *minute* 4 to the end of stimulation, these values progressively and partially returned toward resting values.

In addition, the data were reorganized by summing the 3 FIDs collected during activation on one side and the 3 FIDs obtained during the rest period on the other side. No statistically significant difference was detected for any parameter.

The recovery of PCr was well fitted with a monoexponential function. The τ PCr reached the mean value of 72.2 ± 25.0 s. This τ PCr value was corrected for acidosis by normalizing to the actual cytosolic pH (19) and was then found to be 59.1 ± 19.0 s. This value was

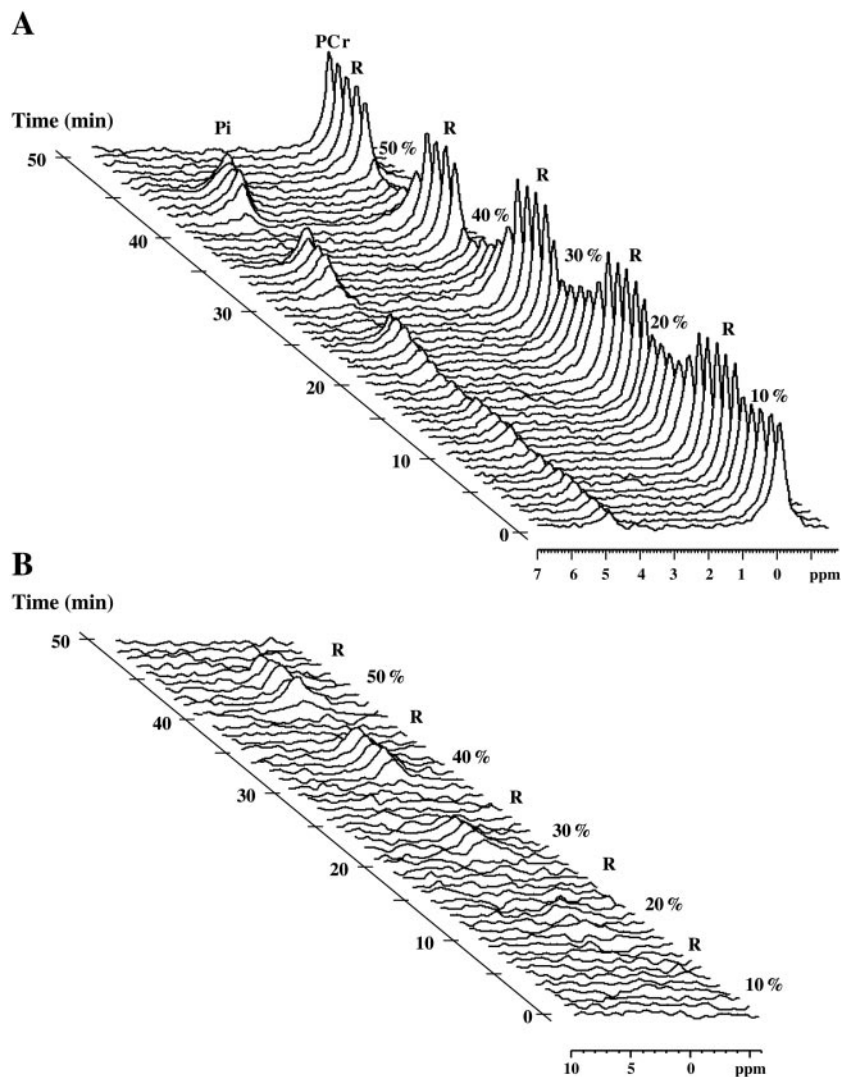


Fig. 2. ^{31}P - (A) and ^1H -NMR (B) spectra in rectus femoris muscle of *subject 1* during the different steps [10, 20, 30, 40, and 50% of quadriceps maximal isometric voluntary torque (QMIVT)] (5 min) and the following recoveries (R) (5 min) of the VC session. ^{31}P spectra are plotted between 7 and -2 parts/million (ppm) relative to phosphocreatine (PCr) and peak assignments are indicated for P_i and PCr.

significantly longer than the τ PCr measured during the VC protocol ($P < 0.05$ with τ PCr of 50% QMIVT, < 0.01 with τ PCr of 30 and 40% QMIVT).

Comparison Between VC and ES

Metabolic stress. Table 1 also contains the ^{31}P - and ^1H -NMRS mean results obtained during ES. When comparing the metabolic stress induced by ES (ES at 5 min and ES-max, where ES-max is the greatest change observed during the ES period) and VC for identical absolute workloads (10% of QMIVT), ES generated a higher metabolic demand than VC for all measured parameters ($P < 0.001$). When comparing the metabolic stress obtained with approximately identical workloads per activated muscle group (10% QMIVT for ES and 30% QMIVT for VC), all parameters showed a higher metabolic solicitation under ES (ES-max), but only pH and PCr depletion differed significantly between contraction modes.

pH-to-[ADP] relationship. We studied the relationship between pH and [ADP] during both exercises for all subjects (Fig. 6A) by taking into account all steps composed of 5-min exercise for the VC protocol and the 13

min of stimulation for the ES protocol. These global relationships were closely fitted with a monoexponential function [$\text{pH} = ae^{-b(\text{ADP})} + c$], showing that the decrease of pH associated with the increase of [ADP] was markedly faster during ES than during VC. The equations fitted to the pooled data were $\text{pH} = 0.52e^{-0.011\text{ADP}} + 6.56$ for VC and $\text{pH} = 0.93e^{-0.142\text{ADP}} + 6.7$ for ES.

P_{O_2} -to-[ADP] relationship. All individual relationships between P_{O_2} and [ADP] were plotted together for both types of exercise (Fig. 6B). The same time points as for the study of the pH-[ADP] relationship were taken into account and were fitted with the same monoexponential function. This relationship (Fig. 6B) showed that the P_{O_2} rate constant appeared lower during ES than during VC. The equations fitted to the pooled data were $\text{P}_{\text{O}_2} = 50e^{-0.143(\text{ADP} - 4.75)} + 5.12$ for VC and $\text{P}_{\text{O}_2} = 50e^{-0.103(\text{ADP} - 4.1)} + 7.37$ for ES. This difference was further substantiated by the comparison of the P_{O_2} measured under the two conditions over the range of ADP activation obtained during ES (10–32 μM) and by taking ADP as covariate: 11.2 ± 0.6 Torr during VC vs. 16.1 ± 0.5 Torr under ES ($P < 10^{-6}$).

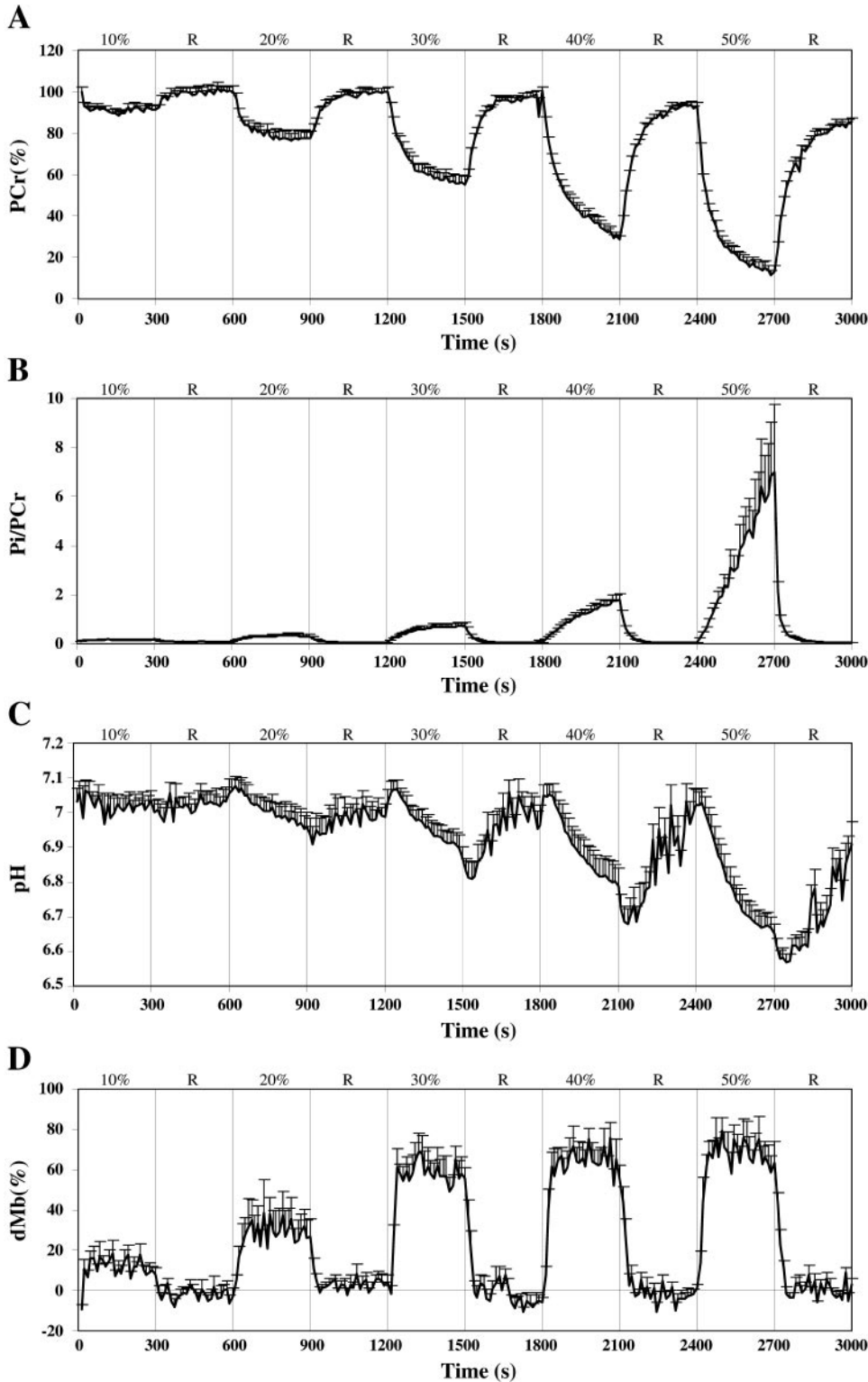


Fig. 3. Mean + SE curve obtained from the individual data during the different steps (10, 20, 30, 40, and 50% QMIVT) and the following recoveries (R) of the VC session for PCr (A), Pi/PCr ratio (B), pH (C), and deoxymyoglobin (dMb; D), respectively.

Mb Quantitation

The mean [Mb] value was 0.23 ± 0.05 mmol/kg.

DISCUSSION

Using a very similar approach to Richardson et al. (39), we investigated the interplay between the cell

energy charge, pH, and oxygenation in exercising skeletal muscle cells. On the basis of this analysis, we further characterized the fundamental differences in energy metabolism between voluntary and electrostimulated contractions. A main purpose of this study was to situate the metabolic stress induced by the ES program (13 min) on a scale of voluntary bouts realized

Table 1. ^{31}P ^1H -NMR interleaved acquisitions

	PCr Depletion, %	P_i/PCr Ratio	pH	Po_2 , Torr
Rest		$0.06 \pm 0.02^{\text{be}}$	$7.03 \pm 0.02^{\text{be}}$	
VC-10%	$6.4 \pm 3.6^{\text{be}}$	$0.13 \pm 0.04^{\text{be}}$	$7.04 \pm 0.07^{\text{be}}$	$36.7 \pm 16.9^{\text{be}}$
VC-20%	$18.6 \pm 7.6^{\text{be}}$	$0.26 \pm 0.12^{\text{be}}$	$6.98 \pm 0.08^{\text{be}}$	$20.2 \pm 15.8^{\text{be}}$
VC-30%	$41.9 \pm 11.0^{\text{c}}$	0.66 ± 0.34	$6.90 \pm 0.09^{\text{be}}$	6.2 ± 3.4
VC-40%	$66.8 \pm 6.3^{\text{bc}}$	1.50 ± 0.55	$6.83 \pm 0.12^{\text{ad}}$	4.9 ± 3.0
VC-50%	$85.2 \pm 8.9^{\text{be}}$	$6.85 \pm 8.61^{\text{be}}$	6.67 ± 0.10	5.1 ± 3.8
Exhaustion	$87.9 \pm 9.1^{\text{be}}$	$10.6 \pm 11.6^{\text{be}}$	6.64 ± 0.11	5.5 ± 3.3
ES 5 min	39.5 ± 15.9	1.15 ± 0.76	6.70 ± 0.11	10.7 ± 12.2
ES-max	53.7 ± 17.8	1.38 ± 1.14	6.69 ± 0.11	5.7 ± 6.0

Values are means \pm SD ($n = 8$). Phosphocreatine (PCr) depletion, P_i/PCr ratio, pH, and Po_2 measured in the rectus femoris at rest, during the voluntary contractions (VC) session, and during the electrical stimulations (ES) session. For the VC session, data represent the last minute of each step performed against gradual workloads corresponding to different percentages (10, 20, 30, 40, and 50%) of the quadriceps maximal isometric voluntary torque (QMIVT). Exhaustion is defined as the maximum load lifted by the volunteers and was 50% of QMIVT for 5 subjects and 60% of QMIVT for the other 3 subjects. During the ES session, the workload was 10% of QMIVT. The mean values measured during *minute 5* of ES are listed (ES 5 min) as well as the greatest changes observed during the ES period (ES-max). Significant difference vs. ES 5 min: $^{\text{a}}P < 0.01$; $^{\text{b}}P < 0.001$. Significant difference vs. ES-max: $^{\text{c}}P < 0.05$; $^{\text{d}}P < 0.01$; $^{\text{e}}P < 0.001$.

against different mechanical loads. We therefore developed a progressive exercise composed of five or six steps. For this to be feasible within a single NMR exam, we decreased the bout duration from 13 to 5 min. In a preliminary study (data not shown), we demonstrated that, for a given mechanical load, results of evaluated parameters were identical after 5 or 13 min of VC.

In a previous study, our group used ^{31}P -NMRS to explore muscle energetics during intermittent tetanic ES of human quadriceps (50). The present protocol is more advanced from a technical standpoint. The key element was the introduction of a new acquisition interface [multiscan control, developed by A. Nauwerth (Bruker, Ettlingen, Germany)], which allows extremely fast interleaving of ^1H - and ^{31}P -NMR acquisi-

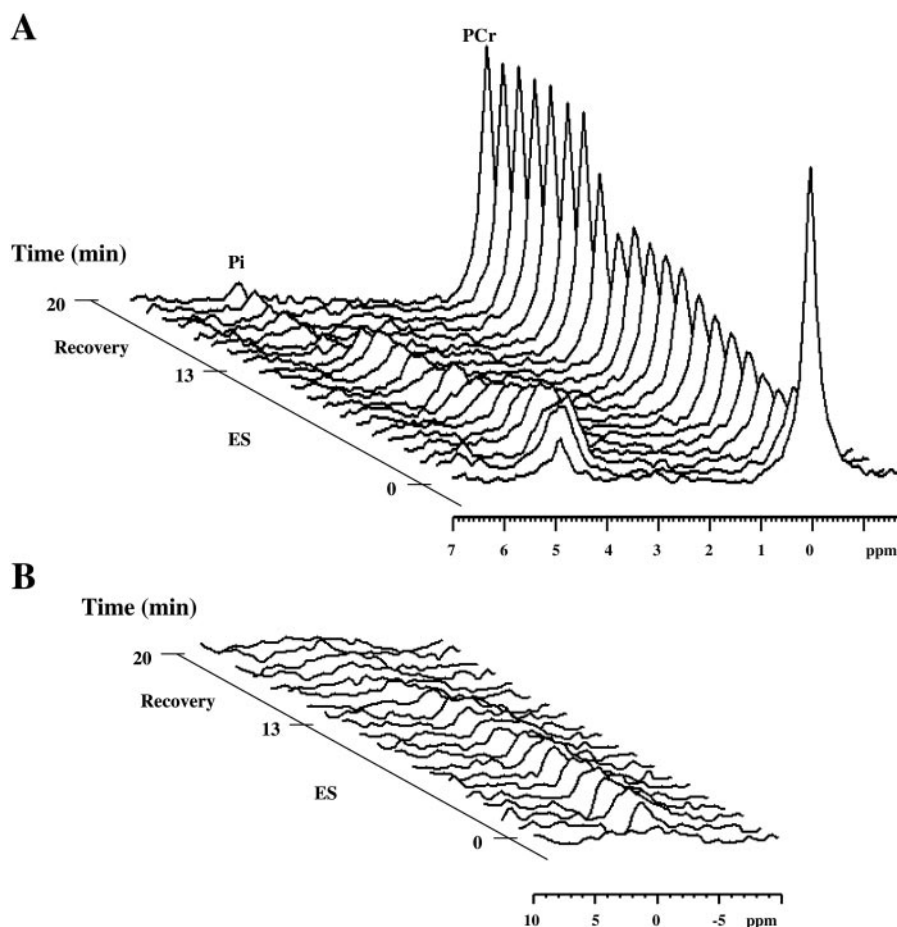


Fig. 4. ^{31}P - (A) and ^1H -NMR (B) spectra in rectus femoris muscle of *subject 1* during intermittent ES (13 min) and recovery (7 min). Spectra are plotted between 7 and -2 ppm, and peak assignments are indicated for P_i and PCr.

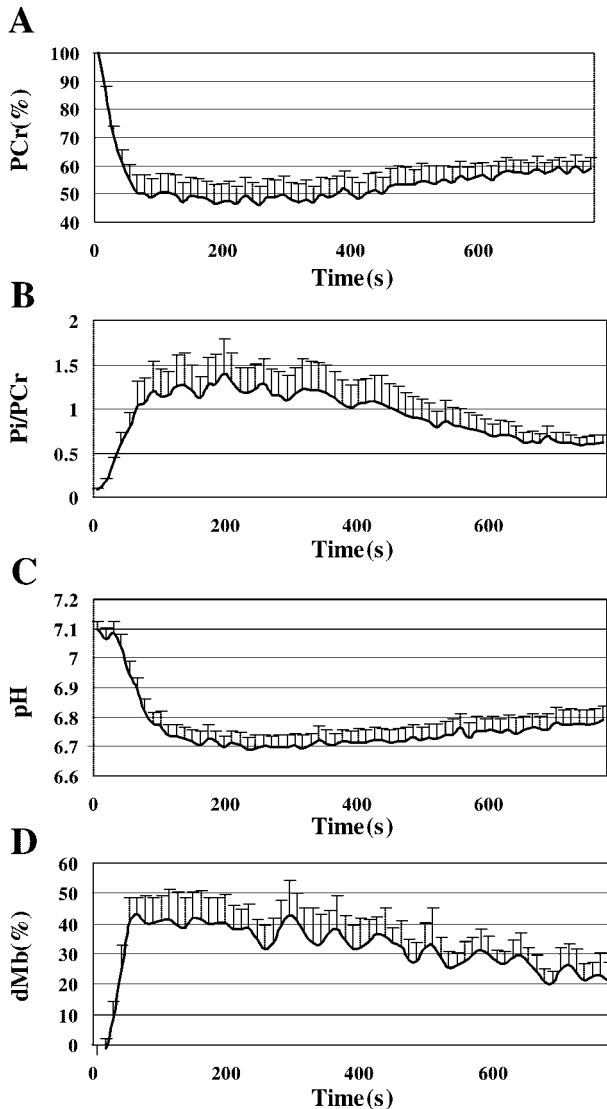


Fig. 5. Mean + SE curve obtained during intermittent ES (0–780 s) from the individual data for PCr (A), Pi/PCr (B), pH (C), and dMb (D), respectively.

tions. The switching was more than fast enough to be disregarded on the time scale at which the metabolic changes occur, and we can consider that muscle oxygenation, high-energy phosphates, and pH were indeed simultaneously monitored. Compared with the previous work, a significant gain in signal to noise was achieved, due to the higher magnetic field (4 T vs. 1.5 T formerly), but also to the considerably improved electronic connections between the electrostimulator and the NMR spectrometer, namely, the quality of the filtering through the Faraday cage. Part of the increase in signal to noise was traded for a better time resolution of the spectra, making it possible here to finely depict the progression of the metabolic changes during the bouts. Finally, the present study employed a simplified experimental setup in terms of number of stimulating electrodes that facilitated data interpretation.

A concern was that the VC session, which was practiced on the day preceding ES, might have influenced

the response to ES. Two subjects performed a second VC protocol after ES. For all steps and for all parameters, the results were comparable to those measured during the first VC protocol ($P > 0.05$). If 30 h after the first VC and 6 h after ES, the results of the second VC are identical to those of the first VC, this indicates that neither VC nor ES had any prolonged cumulative effect. Alternatively, the first VC and ES might have had opposite long-lasting effects. The second hypothesis cannot be ruled out but is unlikely and has no mechanistic support.

VC

The phosphorus metabolites involved in muscle energy production and utilization are related via the creatine kinase reaction. The changes in their relative distribution, as can be detected by ³¹P-NMR, are commonly used as indicators of the level of metabolic activation during exercise (2, 21). At the onset of exercise, there is an immediate breakdown of PCr, which provides the necessary fuel for the first seconds of contraction. The glycolytic pathway then takes over, first as a major ATP producer, then as a minor producer when the mitochondrial oxidative phosphorylations, in response to the rise in ADP, become the predominant source of ATP. Interestingly, the Pi/PCr

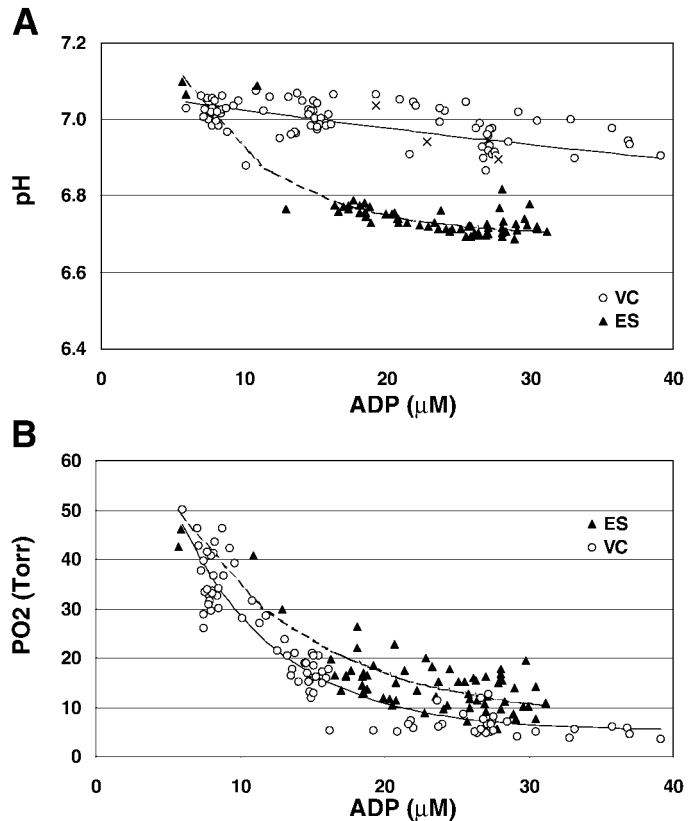


Fig. 6. Fitted curves obtained with pooled individual data for the pH-ADP concentration relationship (A) and the PO₂-ADP concentration relationship (B) during VC and ES. A: x symbols correspond to 3 successive data points collected early into ES, when PCr is rapidly being depleted (phase 1 of exercise) and consequently is buffering pH.

ratio, easily monitored on the ^{31}P spectra, evolves in direct proportion to the cytosolic [ADP], which is itself below the direct detection limits of NMR. The P_i/PCr ratio is most useful to appreciate the mitochondrial respiratory control exerted by ADP (29). In this work, the tight coupling between force development and respiratory control by ADP was again verified by the progressive increase in the P_i/PCr ratio with the stepwise increase in mechanical load. During the last step, the mean PCr depletion and P_i/PCr ratio reached 87.9% and 10.6, respectively. This mean P_i/PCr value appeared very high compared with other reported exercise-induced maximal P_i/PCr ratios (3, 52), confirming that the subjects had indeed exercised until exhaustion. This should be tempered by the fact that P_i/PCr presented a large interindividual variability and was abnormally high during the last step in some subjects because the PCr peak disappeared into the noise.

The decrease in the intracellular pH was also proportional to the increase in force level. It is still common to relate intracellular acidosis to anaerobic lactate production (46). Strictly speaking, this is untrue for two reasons. First, lactate production through glycolysis does not produce protons. The net balance for H^+ is null (9). Second, lactate production in exercising muscles is far from being controlled by hypoxia only (37). The sympathetic tone is a major activator of the glycolytic pathway and of lactate production, independent of the degree of cell oxygenation (18). In reality, intramyocytic acidosis develops when ATP consumption, which is the actual source of protons (15), is not balanced by mitochondrial ATP production, which drains these protons. Once the real origin of protons is made clear, it follows that proton production and [ADP] are related during an aerobic exercise, both with each other and with the mechanical load. This is exactly what was observed in this protocol during VC (see Table 1). The minimal role of cell hypoxia was also exemplified because intracellular pH, which decreased from 6.90 to 6.67 between 30 and 50% maximal VC (MVC), appeared unrelated to intracellular P_i , which remained constant (6.2–5.1 Torr) over this range of mechanical loads.

The decrease in pH during the early phase of recovery of each step results from the rapid resynthesis of PCr, which affects the pH status of the cell by generating protons (45).

A 420-s ischemia of the thigh was used to obtain the maximal Mb desaturation peak, providing a reference for cytoplasmic oxygenation determination. Indeed, it has been demonstrated that desaturation of Mb in human muscle peaked after ~ 6 min of cuff occlusion (51), and this was verified in our laboratory with a stable Mb desaturation for a cuff pressure of ≥ 80 Torr above systolic blood pressure. We found no significant difference between the mean desaturation values calculated at *minutes* 5, 6, and 7 of ischemia (+3 and +2% for *minutes* 6 and 7 vs. *minute* 5, $P = 0.90$). Our values of [Mb] are comparable to previous determinations in

the human calf muscle (5) and in the quadriceps of subjects aged between 19 and 39 yr (31).

During exercise, muscle O_2 consumption ($\dot{V}\text{O}_2$) can increase by adaptations in O_2 supply and by an increase in the capillary-to-cell PO_2 gradient. Increasing perfusion is the natural way to augment O_2 supply and at the same time raise mean capillary PO_2 directly or indirectly via capillary recruitment and associated adaptations of capillary transit time (42). The other possibility for augmenting the transcappillary PO_2 gradient is to decrease intracellular PO_2 to facilitate oxygen diffusion. This was observed here with a progressive fall in intracellular PO_2 between 10 and 30% MVC. The appearance of deoxygenated Mb and thus the fall in intracellular PO_2 even during relatively low work levels (such as 20% MVT) might also have been facilitated by the experimental design (6-s isometric contraction, 6-s rest), with ischemia induced during contraction and incomplete recovery during relaxation. Above 30% MVC, intracellular PO_2 did not, however, decrease any further but rather plateaued at ~ 5 Torr. This agrees with results of Richardson et al. (37–39), who previously studied Mb desaturation during exercise of the quadriceps in trained human volunteers and found that muscle PO_2 deduced from Mb desaturation decreased significantly during exercise, but remained at a constant level of ~ 3 Torr between 30 and 80% maximal $\dot{V}\text{O}_2$. The matter is, however, debated since it was reported that the capillary-to-sarcoplasm PO_2 gradient increased up to maximal $\dot{V}\text{O}_2$ (30). A possible but improbable explanation is that exercise intensity was not high enough in that study; it can always be claimed that the plateau was in fact not reached. In our opinion, a more likely possibility is that different muscle territories may have different regulations of O_2 supply and uptake. The data by Richardson et al. (37–39) and by our group, which are in close agreement and clearly demonstrate a relatively early plateau in Mb desaturation, were collected over the course of a progressive exercise of the quadriceps. The observations by Mole et al. (30) were made on the triceps surae. It is important to note that all investigators have reported a maximum Mb desaturation of ~ 48 –60% during exercise. One can then reformulate the discrepant observations by saying that maximum exercise corresponds to maximum Mb desaturation in the gastrocnemius, whereas exercise can still be intensified in the quadriceps after maximum Mb desaturation is reached.

ES

A main result of this study is that, for an identical mechanical level (10% MVT), ES induced far greater metabolic changes than VC. This pattern is more likely to result in a specific muscle cell recruitment involving a non-steady-state metabolism and early fatigue. The demonstration of this particular pattern of muscle activation is an argument in favor of the combination of ES with VC for the treatment of amyotrophy in the context of rehabilitation. The metabolic changes measured in the present study were more severe than those

of our previous investigation (50) (1.38 vs. 0.46 for the P_i/PCr ratio and 6.69 vs. 6.76 for the pH). This can be explained by a difference in the surface coil position (rectus femoris vs. vastus medialis) and/or by a more important relative loading of the stimulated muscle. Indeed, we used three stimulating electrodes (vastus medialis, vastus lateralis, and rectus femoris) to lift 20% of QMIVT load in the previous study and one stimulating electrode to lift a load of 10% QMIVT in the present study. This was confirmed by the higher current intensity required at the end of the ES program of the present study compared with the previous one (69 vs. 51 mA).

High-energy demand during ES. The first point to be addressed was whether the exaggerated metabolic stress observed under ES resulted from an uneven distribution of the mechanical load and, precisely, from a smaller muscle mass involved during ES compared with VC. The exact proportion of quadriceps involved during the ES protocol applied with only one stimulating electrode positioned on the rectus femoris muscle could not be determined under the present experimental conditions. However, a positron emission tomography (PET) study has demonstrated that approximately one-third of the quadriceps was recruited to lift a load of 10% of QMIVT with one stimulating electrode positioned on the vastus lateralis (49). Consequently, adjusting for work load per unit volume of activated muscle, we focused our attention on the comparison of 10% QMIVT for ES vs. 30% QMIVT for VC. That comparison clearly showed that a greater metabolic stress held, even when the mechanical load was approximately adjusted for the muscle mass, respectively, involved in the two modes.

As a consequence, additional mechanisms must contribute to the exacerbated solicitation in the ES mode, and it is therefore important to consider the particularities in the temporal and spatial recruitment of fibers.

TEMPORAL RECRUITMENT. A light-loaded voluntary exercise principally recruits oxidative type I fibers (16) that depolarize at a low frequency (~15 Hz) (25) in a desynchronized manner (11). In contrast, ES at the same frequency is mechanically less efficient because the synchronous contractions of the depolarized motor axons involve an incomplete temporal recruitment (16). Therefore, a higher stimulation frequency (~50 Hz) is required to improve the mechanical efficiency. However, this increase in the stimulation frequency, which corresponds to a supramaximal temporal recruitment, is linked to a higher metabolic demand (28).

SPATIAL RECRUITMENT. ES preferentially recruits muscle zones near the electrode and this recruitment diminishes proportionally with increasing distance from the electrode (48). A decrease of the mechanical response linked to fatigue of the superficial motor units can only be compensated by an increase of stimulation intensity. This more intense stimulation depolarizes new motor units at a greater distance from the electrode but continues to impose a sustained contractile activity to the superficial motor units, which then

present a certain degree of exhaustion (49). During the ES protocol, what the NMR coil interrogates is a mixture of progressively fatiguing fibers and newly activated ones. The coil geometry makes it predominantly sensitive to muscle fibers contained in a cocentered hemisphere of coil diameter (5 cm). Fibers located further away from the coil, and which are progressively recruited with increasing current intensities, contribute less to the NMR signal to an extent that cannot be precisely assigned in this protocol.

We confirmed that under ES the metabolic demand measured via the high energetic phosphates status (P_i/PCr , pH) was widely out of proportion compared with the VC requiring the same force development. Our data agree with the findings of Ratkevicius et al. (33), who compared ES and VC with ³¹P-NMR in the gastrocnemius and soleus muscles and concluded that the energy costs of force development are higher during electrically induced exercise than during voluntary exercise when continuous contraction of submaximal intensity is performed. VC and functional ES exercises were also compared during dynamic knee-extensor contractions, and glycogen depletion was much higher after ES than VC (22). In addition, we demonstrated that the greater energy charge, which automatically implies specific regulations of energy metabolism, was associated with more profound changes in the level of cytoplasmic oxygenation. However, the present study could not provide direct evidence for the proposed mechanisms.

Preferential recruitment of glycolytic fibers under ES. The construction of the plots of the pH-to-ADP relationship identified another important particularity of the ES mode: a shift in the typology of the fibers preferentially involved during ES. As mentioned above, VC results in a fiber recruitment modulated as a function of motor unit size beginning with the small type I fibers (17), whereas ES of the quadriceps recruits superficial muscle zones that present a predominance of type II fibers (27). This is supported by the study of the pH-ADP relationship. During the gradual VC protocol, we established a reference curve for the pH decrease associated with the increase in [ADP]. The same curve plotted during ES indicated that, for a given solicitation in high-energy phosphates, the electrically contracted muscle was more acidotic. This observation is compatible with a preferential recruitment of type II fibers. Indeed, during classic high-intensity exercise, fast glycolytic muscle fibers become more acidic and more rapidly so than slow oxidative twitches (32). In our experimental conditions, we excluded the hypothesis of a transient impairment of perfusion (53), which might explain the different pH-ADP relationship observed under ES for the following reasons. 1) The PET technique has already established that the ES muscle presents a hyperperfusion compared with the VC muscle (48). 2) One subject performed two steps of the voluntary protocol (10 and 30% QMIVT) under ischemic conditions (data not shown), and the pH-ADP relationship was the same as that during the normal

graded exercise. This result confirmed that during VC the pH-ADP relationship was not perfusion dependent.

Muscle oxygenation during ES. On the basis of mechanical considerations only, muscle cytoplasmic oxygenation appeared altered during ES and might be directly related to a higher muscle $\dot{V}O_2$ in this modality. A previous study of the ES quadriceps with the PET technique has already shown a proportionally high level in the rate of oxygen metabolism (48). The particular contractile activity discussed above remains the most likely explanation for this exaggerated $\dot{V}O_2$ at a low mechanical load.

Muscle PO_2 -ADP relationship under ES. The combination of the simultaneously acquired ¹H and ³¹P data has afforded a better understanding of the muscle cell O_2 status as a function of metabolic stress. The PO_2 -to-ADP relationship shows a slower decline rate of muscle PO_2 during ES than during VC. Thus, for a given metabolic stress, cytoplasm O_2 content appears higher during ES than during VC. These results are compatible with a change in the dynamic equilibrium between O_2 supply and $\dot{V}O_2$ and suggest an upward shift of the O_2 supply- $\dot{V}O_2$ relationship during ES. The observation could be explained by a relative muscle hyperperfusion in the ES muscle. Certainly, muscle is perfused in excess during ES, compared with VC, for a given imposed absolute workload. This was documented by $H_2^{15}O$ PET, which established that the muscular blood flow measured during an ES program reached $\sim 25 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g}^{-1}$ in some regions of the quadriceps (49) and that this value was three times higher than the blood flow measured during a comparable VC of the quadriceps (48). But this would not explain the modified relationship in Fig. 6B. What these curves suggest is that, for a given metabolic stress estimated from the [ADP], muscle is hyperperfused in ES compared with VC. High muscle perfusion relative to the metabolic demand results in a high level of O_2 availability and might therefore increase cytoplasmic oxygenation. Alternatively, it might be argued that fibers closer to the coil fatigued by ES are essentially metabolically recovering, whereas muscle fibers are progressively being activated during VC. So, the ADP to PO_2 would be scanned from left to right during VC and predominantly from right to left during the latter phase of ES. A hysteresis-like effect might then account for the differences in Fig. 6B. However, when considering data acquired during the first 3 min of ES and comparing them with data acquired later into ES, it appears that all ES data belong to the same relationship (not shown).

Exercise Recovery

The postexercise τ PCr provides a most useful index (4). If the acidotic inhibition of creatine kinase is corrected, the τ PCr is independent of the mechanical work and truly reflects the maximal capacity of the mitochondrial oxidative phosphorylation (21). This was illustrated here with the comparison of the τ PCr determined during the recovery phases of the VC ses-

sion. After correction for the degree of acidosis (19), the successive measurements appeared similar and fell within the normal range determined in our laboratory. By contrast, the post-ES τ PCr was prolonged by $\sim 40\%$ compared with post-VC τ PCrs. This is another important argument in favor of a preferential recruitment of type II fibers with lower oxidative capacities during ES.

Conclusion and Perspectives

Not only did this study confirm the important increase in energy demand associated with neuromuscular ES compared with VC, but our results also shed light on specificities of ES contractions that had been poorly recognized or were yet unknown. The protocol was designed in such a way that ES and VC data could be precisely compared, with adequate matching in time and mechanical load. The introduction of heteronuclear interleaved NMR acquisitions was decisive in depicting the particular relationships between intracellular O_2 and energy metabolism during neuromuscular ES. In this context, the significant new contributions were 1) the demonstration of a greater involvement of glycolysis during ES, and, with the construction of the pH-to-ADP relationship, its dissociation from the energy charge (the latter indicating a preferential recruitment of type II fibers); 2) the observation, with ¹H spectroscopy of Mb, of an altered transcellular O_2 gradient that must play a role in facilitating the exacerbated $\dot{V}O_2$ response during ES (48); and 3) the identification of a specific pattern for the relationship between intramyocytic PO_2 and ADP during ES. After the intracellular PO_2 had been normalized to the actual load imposed on the energy metabolism, the O_2 gradient appeared to be reduced during ES and not increased, as one would have intuitively hypothesized.

The lead for further investigation is certainly to explore this hypothesis of hyperperfusion under ES with the same matching of measurements as was done here for the exploration of oxygenation and high-energy phosphate metabolism. Muscle perfusion can indeed be monitored in a completely noninvasive mode with new NMR imaging sequences by using arterial water as a natural endogenous tracer and known as "arterial spin-labeling" sequences (13, 26, 36). They provide perfusion maps with high temporal (in the second range) and spatial (millimetric) resolutions, and as we have already shown, these arterial spin-labeling sequences can be incorporated into interleaved acquisition schemes, together with ¹H- and ³¹P-NMRS (5, 35).

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