Cardiovascular and cerebral hemodynamics during exercise and recovery in obese individuals as a function of their fitness status

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Abstract
The aim of this study was to compare cardiovascular hemodynamics and cerebral oxygenation/perfusion (COP) during and after maximal incremental exercise in obese individuals according to their aerobic fitness versus age-matched healthy controls (AMHC). Fifty-four middle-aged obese (OB) and 16 AMHC were recruited. Maximal cardiopulmonary function (gas exchange analysis), cardiac hemodynamics (impedance cardiography), and left frontal COP (near-infrared spectroscopy: NIRS) were measured continuously during a maximal incremental ergocycle test. During recovery, reoxygenation/perfusion rate (ROPR: oxyhemoglobin: \( \Delta O_2Hb \), deoxyhemoglobin: \( \Delta HHb \) and total hemoglobin: \( \Delta tHb \); with NIRS) was also measured. Obese participants (OB, \( n = 54 \)) were divided into two groups according to the median \( \_\_VO_2 \) peak: the low-fit obese (LF-OB, \( n = 27 \)) and the high-fit obese (HF-OB, \( n = 27 \)). During exercise, end tidal pressure of CO2 (PETCO2), and COP (\( \Delta O_2Hb \), \( \Delta HHb \) and \( \Delta tHb \)) did not differ between groups (OB, LF-OB, HF-OB, AMHC). During recovery, PETCO2 and ROPR (\( \Delta O_2Hb \), \( \Delta HHb \) and \( \Delta tHb \)) did not differ between the groups (OB, LF-OB, HF-OB, AMHC). During exercise and recovery, cardiac index was lower (\( P < 0.05 \)) and systolic blood pressure was higher during exercise in the OB, LF-OB and HF-OB groups versus AMHC (\( P < 0.05 \)). When compared to AMHC, obese individuals (OB, LF-OB, HF-OB) have a similar cerebral vasoreactivity by CO2 and cerebral hemodynamics during exercise and recovery, but a higher systolic blood pressure during exercise. Higher fitness in obese subjects (HF-OB) seems to preserve their cardiopulmonary and cardiac function during exercise and recovery.

Introduction
The prevalence of obesity in adults has dramatically increased, reaching 25–39.5% in Canada and USA (Nguyen and Lau 2012; Ogden et al. 2013). Obesity is associated with important comorbidities like cardiovascular diseases, hypertension and diabetes, but also with a higher risk of cerebrovascular diseases such as stroke, dementia and/or Alzheimer disease (Wilson et al. 2008; Toda et al. 2014). Obesity is associated with resting cerebral abnormalities that include: increased brain arterial stiffness/pulsatility, reduced cerebral endothelial...
function, reduced cerebral blood flow and cardiac diastolic and/or systolic dysfunction (Furtner et al. 2009; Toda et al. 2014). Early in obesity (younger adults), there is an adaptive cardiac mechanism, with an increased blood volume, cardiac preload and enlargement and thickening of the left ventricles measured at rest, therefore resting systolic function can be increased and/or preserved (Artham et al. 2008; Vella et al. 2012; Crendal et al. 2013), this could have an impact on cardiovascular function during exercise in older obese adults. Some previous studies (with only one reported in middle-aged obese adults) demonstrated a reduced normalized maximal aerobic power (\( \dot{V}O_2 \) peak divided by lean body mass) (Vella et al. 2012; Fournier et al. 2014) associated with an impaired cardiac systolic function (Vella et al. 2012; Fournier et al. 2014) and muscle oxygen extraction (\( C(a-v)O_2 \)) (Vella et al. 2011, 2012; Fournier et al. 2014) in obese subjects as compared to age-matched nonobese healthy controls (AMHC) during incremental exercise. Similarly to the cardiovascular function, very few studies are reported on the impact of obesity on cerebral hemodynamics during exercise and recovery, and none were performed in older obese adults. Conflicting results on cerebral hemodynamics during exercise were recently reported in young obese men versus AMHC (Cavuoto and Maikala 2015, 2016). One study reported a similar cerebral oxygenation-perfusion (measured by near-infra red spectroscopy: NIRS) during sub-maximal cycling exercise in young obese men versus AMHC (Cavuoto and Maikala 2016), while the same authors showed a reduced cerebral oxygenation (measured by NIRS) during repetitive incremental lifting to exhaustion in a similar cohort (Cavuoto and Maikala 2015). These discrepant results might come from confounding variables. In healthy subjects, principal cardiovascular parameters that modulate cerebral oxygenation-perfusion (COP) during exercise are arterial blood pressure, carbon dioxide (\( \text{PaCO}_2 \)) and cardiac output (Ogoh and Ainslie 2009). As well, other factors such as cardiovascular disease and aerobic fitness (\( \dot{V}O_2 \text{peak} \)) can influence COP during exercise. For example, a higher COP has been observed in the higher fit (\( \dot{V}O_2 \text{peak} \)) younger and older healthy subjects (Rooks et al. 2010; Bailey et al. 2013; Brugniaux et al. 2014). As well, cardiac patients have a lower COP during exercise and recovery compared to healthy controls, in relation to a reduced \( \dot{V}O_2 \text{peak} \) and cardiac function (Koike et al. 2004a, 2004b; Fu et al. 2013; Gayda et al. 2016). Obesity in older adults can be associated with a reduced \( \dot{V}O_2 \) peak and impaired cardiac systolic function (Vella et al. 2012; Fournier et al. 2014) which could reduce COP during exercise and its recovery, particularly in less fit subjects.

A better understanding of the interrelationships between \( \dot{V}O_2 \) peak, COP, cardiovascular hemodynamics and fitness level during and after exercise might provide promising future intervention avenues for individuals with obesity. To the best of our knowledge, no previous study has compared cardiovascular hemodynamics and COP during maximal incremental exercise and recovery in older obese subjects. In addition, the influence of initial aerobic fitness level (\( \dot{V}O_2 \) peak) on cardiovascular hemodynamics and COP during exercise and recovery is unknown in older obese subjects. Therefore, the aim of this study was to compare cardiovascular hemodynamics and COP during and after maximal incremental exercise in obese individuals compared to nonobese aged-matched healthy controls (AMHC) while taking into account aerobic fitness level (\( \dot{V}O_2 \) peak). We hypothesized that cardiovascular hemodynamics and COP during maximal exercise and recovery will be reduced in the obese subjects, particularly the less fit.

**Methods**

**Subjects**

A total of 70 adults were enrolled from the Cardiovascular Prevention and Rehabilitation Centre of the Montreal Heart Institute, including 16 AMHC (64 ± 4 years) and 54 obese subjects (OB) (62 ± 6 years). The whole OB group (n = 54) was divided into two groups according to their median \( \dot{V}O_2 \) peak: the low-fit obese group (LF-OB: n = 27) and the high-fit obese group (HF-OB: n = 27). For AMHC, inclusion criteria were: age >18 years, normal adiposity (<25% for men and <35% for women) (Cornier et al. 2011; Dalzill et al. 2014), no cardiovascular (CV) risk factors and no evidence of cardiovascular disease. For OB, inclusion criteria were: age >18 years, to be obese defined by a body fat mass percentage >25% for men and >35% for women (Cornier et al. 2011; Dalzill et al. 2014), no evidence of cardiovascular disease. The CV risk factors were defined as follows (Dalzill et al. 2014): diabetes was defined as a prior diagnosis of diabetes along with a fasting glucose >7.1 mmol/L and an HbA1c level >0.06 or a treatment with an hypoglycemic agent. Hypertension was defined as a prior diagnosis of hypertension with blood pressure >150/85 mm Hg or antihypertensive treatment. Active smoking was defined as smoking ≥1 cigarette, cigar, or pipe per day. Dyslipidemia was defined as total cholesterol ≥6.2 mmol/L, low-density lipoprotein cholesterol ≥4.2 mmol/L, or a total/high-density lipoprotein cholesterol ratio ≥4.7 or statin treatment. Exclusion criteria for OB and AMHC were: recent acute

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coronary syndrome (<3 months), significant resting electrocardiogram (ECG) abnormality, history of ventricular arrhythmias or congestive heart failure, uncontrolled hypertension, recent bypass surgery intervention <3 months, recent percutaneous transluminal coronary angioplasty <6 months, left ventricular ejection fraction <45%, pacemaker or implantable cardioverter defibrillator, recent modification of medication <2 weeks, and musculoskeletal conditions making exercise ergocycle contraindicated (Dalzill et al. 2014). All subjects underwent a baseline evaluation that included a medical history, a physical examination with measurement of height and weight, body composition (bioimpedance, Tanita, model BC418, Japan) and fasting blood sample (glucose and lipid profile) (Dalzill et al. 2014; Drigny et al. 2014). They performed a maximal cardiopulmonary exercise test (CPET) with continuous measurement of gas exchange, cerebral hemodynamics with NIRS and cardiac hemodynamics (impedance cardiography) (Gayda et al. 2012, 2016; Gremeaux et al. 2012; Drigny et al. 2014). All participants gave their written informed consent and the protocol was approved by the Ethics Committee of Montreal Heart Institute. The study was registered on ClinicalTrials.gov under identifier number: NCT03018561.

**Measurements**

**Maximal cardiopulmonary exercise testing**

This test was performed on an ergocycle (Ergoline 800S, Bitz, Germany), with an individualized protocol that included: a 3-min warm up at 20 Watts, followed by a power increase in 10 to 20 Watts/min until exhaustion at a pedaling speed > 60 rpm as previously published (Drigny et al. 2014; Gayda et al. 2016). Gas exchanges were measured continuously at rest (during 3 min), during exercise, and recovery using a metabolic system (Oxycon Pro, Jaeger, Germany) as previously published. The calibration of the flow module was accomplished by introducing a calibrated volume of air at several flow rates with a 3-liter pump. Gas analyzers were calibrated before each test using a standard certified commercial gas preparation (O2: 16%; CO2: 5%). Data were measured every four respiratory cycles during testing and then were averaged every 15 sec for minute ventilation (VE, in L/min, BTPS), oxygen uptake (VO2, in L/min, STPD), carbon dioxide production (VCO2, in L/min, STPD), end tidal pressure of CO2 (PETCO2: mmHg) (Drigny et al. 2014; Gayda et al. 2016). Maximal exercise test lasted until the attainment of one of the two primary maximal criteria: (A) a plateau of VO2 peak despite an increase in cadence, (B) R.E.R > 1.1 and one of the two secondary maximal criteria: (C) measured maximal heart rate attaining 95% of age-predicted maximal heart rate, (D) inability to maintain the cycling cadence, (E) subject exhaustion with cessation caused by fatigue and/or other clinical symptoms (dyspnea, abnormal BP responses) or ECG abnormalities that required exercise cessation. The ventilatory threshold was determined using a combination of the V-slope, ventilatory equivalents, and end-tidal oxygen pressure methods (Gaskill et al. 2001). The highest VO2 peak value reached during the exercise phase of each test was considered as the VO2 peak and peak power output (PPO) was defined as the power output reached at the last fully completed stage (Drigny et al. 2014; Gayda et al. 2016).

**Cardiac hemodynamics**

Cardiac hemodynamics were measured continuously at rest (during 3 min), during exercise and recovery using a noninvasive impedance cardiography device (PhysioFlow®, Enduro model, Manatec, France), previously found to be valid, accurate, and reproducible at rest and during exercise in healthy subjects and coronary patients (Charloux et al. 2000; Richard et al. 2001; Vella et al. 2009, 2012; Drigny et al. 2014; Gayda et al. 2016). Data were averaged every 15 consecutive heartbeats for cardiac index (CI: in L/min/m2), stroke volume index (SVi: in mL/m2), heart rate (in beats/min), end diastolic and systolic volume index (EDVi and ESVi: in ml/m2), left cardiac work index (LCWi: in kg.m/m2) and systemic vascular resistance index (SV Ri: in dynes/s/cm5/m2) (Gayda et al. 2012, 2016; Drigny et al. 2014).

**Cerebral oxygenation/perfusion (COP)**

The COP was measured using a near-infrared spectroscopy (NIRS) system (Oxymon Mk III, Artinis Medical, Netherlands) during maximal exercise and recovery (Gremeaux et al. 2012; Drigny et al. 2014; Gayda et al. 2016). Optodes were placed on the left prefrontal cortical area between Fp1 and Fp3, according to the modified international EEG 10-20 system (Gremeaux et al. 2012; Drigny et al. 2014; Gayda et al. 2016). Relative concentration changes (Δμmol/L) were measured from resting baseline of oxyhemoglobin (ΔO2Hb), deoxyhemoglobin (ΔHHb), total hemoglobin (ΔtHb = ΔO2Hb + ΔHHb) (Drigny et al. 2014; Gayda et al. 2016). The baseline period for exercise was set at the end of the 3-min resting period, defined as 0 μmol/L (Drigny et al. 2014; Gayda et al. 2016). For the recovery period, the reference point (0 μmol/L) was set at the immediate start of the recovery period. Therefore, the cerebral re-oxygenation/perfusion rate (ROPR) was defined by post-exercise variation in the ΔO2Hb, ΔHHb and ΔtHb. Data were displayed in real time and stored on disk for off-line analysis (Drigny et al. 2014).
Statistical analysis

Results are presented as mean ± standard deviation except where otherwise indicated. Statistical analysis was performed using Statview software 5.0 (SAS, Cary) and GraphPad Prism 7.02 (GraphPad Software, Inc., La Jolla). Normal Gaussian distribution of the data was verified by the Shapiro–Wilk test. A one-way ANOVA (groups) was used to compare maximal cardiopulmonary and hemodynamics parameters between: (1) AMHC and OB group and (2) AMHC vs. LF-OB and HF-OB groups. A two-way ANOVA (groups x time) with repeated measure for time was performed to compare PETCO2, hemodynamics (CI, SBP, DBP) and cerebral NIRS parameters (ΔO2Hb, ΔHHb, ΔtHb) during exercise and recovery between: (1) AMHC and OB group and (2) AMHC versus LF-OB and HF-OB groups. A two-way ANOVA (groups x time) with repeated measure for time was performed to compare PETCO2 and hemodynamics (CI, SBP, DBP) during exercise and recovery between obese subjects without medication and those taking medication. A Scheffé post hoc test was used to localize differences. Relationships between VO2 peak, ventilatory and cardiovascular parameters at peak effort were assessed with a Pearson coefficient of correlation (R). Statistical significance was set at P < 0.05 level for all analysis.

Results

Clinical and anthropometric characteristics

Table 1 describes the clinical and anthropometric characteristics of the AMHC, OB, LF-OB and HF-OB groups.

As expected, the prevalence of cardiovascular risk factors was higher in the three obese groups (OB, LF-OB, HF-OB) versus AMHC for hypertension (51–55%), dyslipidemias (18–62%) and diabetes (22–59%). Regarding body composition, body mass, BMI, waist circumference and fat mass parameters were higher in the three obese groups (OB, LF-OB, HF-OB) versus AMHC (P < 0.001). Medication use was higher in the three obese groups (OB, LF-OB, HF-OB) particularly for statins, angiotensin receptor blockers and ACE inhibitors. Fasting glucose was higher in OB and LF-OB versus AMHC (P < 0.01), HDL-cholesterol and LDL-cholesterol were lower and triglycerides higher in the three obese groups versus AMHC (P < 0.01).

Cardiopulmonary exercise testing parameters

The cardiopulmonary exercise testing parameters measured at rest, ventilatory threshold (VT) and peak effort are described in details in Table 2. Resting HR and SBP were higher in the three obese groups versus AMHC (P < 0.05). VO2 uptake and power at VT were higher in AMHC versus OB and LF-OB (P < 0.001). VO2 peak, % of VO2 peak predicted and peak power were higher in AMHC versus the OB and LF-OB (P < 0.05). VE peak, % of VE peak predicted and tidal volume (TV) were lower in LF-OB versus AMHC and HF-OB (P < 0.05). Breathing frequency (BF) was higher in HF-OB versus LF-OB (P < 0.05). At peak effort, cardiac output (CO), cardiac index (CI), stroke volume index (SVi), end diastolic and systolic volume (EDVi, ESVi) and systemic vascular resistance index (SVRI) did not differ between groups. Peak HR was lower in LF-OB versus AMHC and HF-OB (P < 0.05) and heart rate recovery (ΔHRR at 1 min) was higher in HF-OB versus LF-OB (P < 0.05). Relationship between VO2 peak, ventilatory and cardiovascular parameters (measured at peak effort) are described in Table 3. In AMHC, VO2 peak was significantly correlated with ventilation (VE), breathing frequency (BF), cardiac output (CO), cardiac index (CI), end diastolic volume index (EDVi), end systolic volume index (ESVi) and left cardiac work index (LCWi). In obese subjects (OB), VO2 peak was significantly correlated with ventilation (VE), tidal volume (TV), breathing frequency (BF), cardiac index (CI) and left cardiac work index (LCWi).

End tidal pressure of CO2, cardiac index and blood pressure during exercise and recovery

Figures 1–4 describe end tidal pressure of CO2, cardiac index, systolic and diastolic blood pressure during exercise and recovery. During exercise, PETCO2 did not differ
among OB, LF-OB and HF-OB groups versus AMHC (Fig. 1 and 2). During exercise, cardiac index did not differ among OB and AMHC (Fig. 1) but was higher in AMHC and HF-OB versus LF-OB at 50%, 75% and 100% of PPO (P < 0.05, Fig. 2). During exercise, SBP was higher at 25%, 50%, and 100% of PPO in OB and in LF-OB versus AMHC (P < 0.05) and higher at 25% and 100% of PPO in HF-OB versus AMHC (Figs. 1 and 2). During recovery, PECTCO₂, SBP and DBP did not differ among the groups (OB, LF-OB, HF-OB and AMHC) (Figs. 3 and 4). During recovery, cardiac index was lower in OB (at 0 sec) and in LF-OB (from 0 to 120 sec) as compared to AMHC and HF-OB (P < 0.05) (Figs. 3 and 4). During exercise and recovery, PETCO₂, SBP and DBP (P > 0.05) did not differ between obese subjects taking medication versus those without medication. During exercise and recovery, cardiac index was lower (P < 0.01) in obese subjects taking medication versus those without medication.

**Left prefrontal NIRS parameters during exercise and recovery**

Figure 5 describes left prefrontal NIRS parameters during exercise in AMHC, OB, LF-OB and HF-OB. During exercise, no differences were found for ΔO₂Hb, ΔHHb and ΔHb between AMHC and OB, LF-OB and HF-OB (Fig. 5). Figure 6 describes left prefrontal NIRS parameters during exercise and recovery among AMHC, OB, LF-OB and HF-OB.
parameters during recovery in AMHC, OB, LF-OB and HF-OB. During recovery, no differences were found for ΔO₂Hb, ΔHHb and ΔHb between AMHC and OB, LF-OB and HF-OB (Fig. 6).

### Discussion

### Major findings

The main findings were: (1) Compared to AMHC, obese subjects (OB) have a lower VO₂ peak, higher systolic blood pressure, but similar cardiac output, cerebral vasoreactivity by CO₂ (PETCO₂) and cerebral oxygenation/perfusion during incremental maximal exercise. (2) During recovery, obese subjects (OB) had lower cardiac index (only at 0 min) but a similar PETCO₂, CO and cerebral re-oxygenation/perfusion rate (ΔO₂Hb, ΔHHb) compared to AMHC. (3) During exercise, the LF-OB group showed a lower cardiac output, higher SBP but similar cerebral vasoreactivity by CO₂ (PETCO₂) and cerebral oxygenation/perfusion compared to the other two groups (AMHC, HF-OB). (4) During exercise, the HF-OB group had higher SBP but similar cardiac output, cerebral vasoreactivity by CO₂ (PETCO₂) and cerebral oxygenation/perfusion compared to the other two groups (AMHC, HF-OB). (5) During recovery, the

### Table 2. Cardiopulmonary and hemodynamic variables at rest and during exercise testing in aged-matched healthy controls (AMHC), obese subjects (OB), obese low-fit (OB-LF) and obese high-fit (OB-HF) groups.

| Cardiopulmonary and hemodynamic variables | AMHC (n = 16) | OB (n = 54) | OB-LF (n = 27) | OB-HF (n = 27) | AMHC vs. OB | OB-LF vs. OB-HF |
|------------------------------------------|--------------|-------------|---------------|---------------|-------------|-----------------|
| Rest                                      |              |             |               |               |             |                 |
| Resting heart rate                        | 63 ± 7ª,†    | 77 ± 14     | 76 ± 15ª,‡    | 77 ± 13ª,†    | 0.0006      | 0.0031          |
| Rest SBP (mmHg)                           | 119 ± 15ª,†  | 130 ± 11    | 130 ± 13ª*    | 129 ± 9ª*     | 0.0023      | 0.0089          |
| Rest DBP (mmHg)                           | 73 ± 10      | 75 ± 12     | 74 ± 16       | 75 ± 8        | 0.6203      | 0.8312          |
| At ventilatory threshold                 |              |             |               |               |             |                 |
| VO₂ uptake (ml/min/LBM)                  | 33.3 ± 5.2ª,‡| 27.4 ± 5.7  | 22.9 ± 3.6ª,‡ | 31.4 ± 4.0ª,‡ | <0.0001     | 0.0009          |
| Power (Watts)                             | 148 ± 43ª,‡  | 110 ± 43    | 83 ± 28ª,‡    | 135 ± 39ª,‡   | 0.0050      | <0.0001         |
| Rest                                       |              |             |               |               |             |                 |
| Resting heart rate                        | 63 ± 7ª,†    | 77 ± 14     | 76 ± 15ª,‡    | 77 ± 13ª,†    | 0.0006      | 0.0031          |
| Rest SBP (mmHg)                           | 119 ± 15ª,†  | 130 ± 11    | 130 ± 13ª*    | 129 ± 9ª*     | 0.0023      | 0.0089          |
| Rest DBP (mmHg)                           | 73 ± 10      | 75 ± 12     | 74 ± 16       | 75 ± 8        | 0.6203      | 0.8312          |
| At ventilatory threshold                 |              |             |               |               |             |                 |
| VO₂ uptake (ml/min/LBM)                  | 33.3 ± 5.2ª,‡| 27.4 ± 5.7  | 22.9 ± 3.6ª,‡ | 31.4 ± 4.0ª,‡ | <0.0001     | 0.0009          |
| Power (Watts)                             | 148 ± 43ª,‡  | 110 ± 43    | 83 ± 28ª,‡    | 135 ± 39ª,‡   | 0.0050      | <0.0001         |
| Group effect: aAMHC versus OB, bAMHC versus OB-LF, cAMHC versus OB-HF, dOB-LF versus OB-HF. |              |             |               |               |             |                 |

SBP, systolic blood pressure; DBP, diastolic blood pressure; LBM, lean body mass; R.E.R, respiratory exchange ratio; TV, tidal volume; BF, breathing frequency; CI, cardiac index; C(a-v)O₂, arterio venous difference; SVi, stroke volume index; LCWi, left cardiac work index; SVRi, systemic vascular resistance index; HR, heart rate; HRR, heart rate recovery.

Group effect: *p < 0.05, †p < 0.01, ‡p < 0.001, §p < 0.0001.
Table 3. Correlation between VO₂ peak, pulmonary and cardiovascular parameters (at peak) in aged-matched healthy controls (AMHC) and obese subjects (OB).

| Parameter       | AMHC     | OB       |
|-----------------|----------|----------|
| VE              | $R = 0.66, P = 0.0085$ | $R = 0.64, P < 0.0001$ |
| VT              | $R = 0.17, P = 0.5676$ | $R = 0.43, P = 0.0011$ |
| Bf              | $R = 0.56, P = 0.0351$ | $R = 0.39, P = 0.0035$ |
| CO              | $R = 0.69, P = 0.0019$ | $R = 0.25, P = 0.0595$ |
| CI              | $R = 0.67, P = 0.0031$ | $R = 0.29, P = 0.0312$ |
| C(a-v)O₂        | $R = -0.24, P = 0.3744$ | $R = 0.09, P = 0.4986$ |
| SVi             | $R = 0.36, P = 0.1640$ | $R = 0.03, P = 0.7880$ |
| EDVi            | $R = -0.53, P = 0.0308$ | $R = -0.02, P = 0.8871$ |
| ESVi            | $R = -0.60, P = 0.0112$ | $R = -0.03, P = 0.8160$ |
| LCWi            | $R = 0.64, P = 0.0060$ | $R = 0.28, P = 0.0338$ |
| SBP             | $R = 0.08, P = 0.7811$ | $R = 0.01, P = 0.9099$ |
| DBP             | $R = 0.14, P = 0.6346$ | $R = 0.14, P = 0.2989$ |

Vemax, maximal ventilation; TV, tidal volume; Bf, breathing frequency; CO, cardiac output; CI, cardiac index; C(a-v)O₂, arteriovenous difference; SVi, stroke volume index; EDVi, end diastolic volume index; ESVi, end systolic volume index; LCWi, left cardiac work index; SBP, systolic blood pressure; DBP, diastolic blood pressure.

LF-OB and HF-OB had similar cerebral vasoreactivity by CO₂ (PETCO₂), blood pressure and cerebral re-oxygenation/perfusion rate (ΔO₂Hb, ΔtHb) compared to AMHC.

Only cardiac output was lower in the LF-OB during recovery versus the other two groups (AMHC, HF-OB).

Although there were group differences in certain cardiovascular measures, cerebral hemodynamics during exercise and recovery were not different between obese groups (OB, LF-OB, HF-OB) and AMHC. To the best of our knowledge, this study is the first to integrate a simultaneous measure of cerebral hemodynamics and their determinants (PETCO₂, cardiac output and blood pressure) during incremental maximal exercise and its recovery in older obese subjects with different level of aerobic fitness. This study underlies the importance of aerobic fitness in obese subjects and its protective effects on cardiovascular function during exercise and recovery.

**Cardiopulmonary and hemodynamic variables during exercise**

Compared to AMHC, obese subjects (OB) and low-fit obese (LF-OB) showed a lower maximal aerobic power (VO₂ peak) and peak power output. As well, the LF-OB had lower peak ventilatory function versus AMHC. The lower VO₂ peak (normalized by LBM) found in OB and LF-OB is in agreement with one previous study (Fournier et al. 2014) but is inconsistent with results from two other studies (Vella et al. 2011, 2012). The C(a-v)O₂ between our groups (OB, LF-OB, HF-OB and AMHC)

Figure 1. PETCO₂, cardiac index, systolic and diastolic blood pressure during exercise in aged-matched healthy controls (AMHC) and obese subjects (OB). ANOVA effect: A=group, B=time, C=interaction; Post hoc group effect: *$P < 0.05$. 

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was not different which is in disagreement with previous studies (Vella et al. 2011, 2012; Fournier et al. 2014). An impaired muscle oxygen extraction observed in previous studies was proposed to be due to a lower mitochondrial density/function, oxygen transport capacity and to endothelial dysfunction (Vella et al. 2011, 2012).
lower \( \dot{V}O_2 \) peak particularly in LF-OB could be explained by a combined reduced pulmonary function (VE and TV) and maximal cardiac index compared to AMHC (Table 2 and Fig. 1 to 4). Therefore, high aerobic fitness seemed to be a protective factor regarding impairment of pulmonary and cardiac function in the HF-OB group.
Compared to AMHC, the three obese groups presented a similar maximal indexed cardiac output and stroke volume at peak effort, with a trend \((P = 0.051)\) for lower CImax in LF-OB (Table 2). However, low-fit obese (LF-OB) showed a reduced cardiac index during incremental exercise (50–100% of PPO) as compared to AHMC and HF-OB (Fig. 2). Similar indexed end diastolic and systolic volumes (ESVi and EDVi) and systemic vascular resistance were shown among obese groups at peak exercise versus AMHC. Conflicting results have been reported on cardiac index during exercise in obese subjects. One study (Vella et al. 2012) reported higher cardiac index (normalized by resting HR and body surface area) during submaximal exercise and similar maximal cardiac index between young obese and nonobese controls. A second study reported lower cardiac index during exercise in obese subjects. One study (Schuster et al. 2012; Vella et al. 2012; Fournier et al. 2014). The similar cardiac index in the HF-OB during incremental exercise (Fig. 2) as compared to AMHC suggests that a high aerobic fitness \((\dot{V}O_2\text{peak})\) in obese subjects may normalize and preserve cardiac function (Schuster et al. 2012). This protective effect of fitness on cardiac function in obese subjects is clinically relevant, and may protect them from cardiovascular diseases such as heart failure for example. In our subanalysis, this positive effect was reinforced by the fact that obese subjects taking medication had lower cardiac function during exercise and recovery versus the obese subjects not taking medication. This may reflect that obese subjects taking medication may have a higher cardiovascular risk profile (Table 1) and therefore a lower cardiac function as compared to obese subjects not taking medication. Previous studies indicate that aerobic exercise training reduces resting end systolic volumes (Schuster et al. 2012) and improves systolic and/or diastolic function at rest (Ingul et al. 2010; Schuster et al. 2012; Hollekim-Strand et al. 2014), less is known about the effects of those intervention on cardiac function during exercise.
Cardiac and cerebral hemodynamics during and after exercise

During exercise, cerebral oxygenation/perfusion was similar between the obese groups (OB, LF-OB, HF-OB) and AMHC for all intensities. Our results are in agreement with a previous study showing similar COP (measured by NIRS) during submaximal cycling exercise between young obese adults and nonobese controls (Cavuoto and Maikala 2016). Previous findings in healthy young adults demonstrated a higher COP in the fittest subjects (Brugniaux et al. 2014; Oussaidene et al. 2015), but this effect was not found in our HF-OB group. Another study showed a reduced cerebral oxygenation (measured by NIRS) in young obese adults during repetitive incremental lifting to exhaustion as compared to nonobese controls (Cavuoto and Maikala 2015). Therefore, aging (Fisher et al. 2013), lower aerobic fitness (Rooks et al. 2010; Brugniaux et al. 2014; Oussaidene et al. 2015) and cardiac disease (Koike et al. 2004a, 2004b; Fu et al. 2013) were shown to reduce COP during exercise. To explain similar COP in obese groups during exercise, variables implicated in cerebral hemodynamics regulation during exercise (PETCO₂, cardiac output and blood pressure) were analyzed (Ogoh and Ainslie 2009). First, it is to note that CO₂ (reflected by PETCO₂) is a powerful vasodilator of cerebral vessels during exercise and that this variable was not different among the obese groups and healthy controls (Fig. 1–2). Secondly, systolic blood pressure during exercise was higher in obese groups (Fig. 1–2) and therefore would have helped to maintain perfusion particularly in LF-OB despite a lower cardiac index during exercise (Fig. 1–2). In addition, we may speculate that other factors, such as hematological ones and inter-individual variability in NIRS could have influenced our results in our obese subjects. For example, higher blood volume and hemoglobin concentration have been previously reported in obese subjects (Vella et al. 2012; Kishi et al. 2014), and could be responsible for a similar COP reported during exercise in the obese groups but this requires further experimentation.

During recovery, cerebral re-oxygenation/perfusion rate (ROPR) was also similar in the obese groups (OB, LF-OB and HF-OB) as compared to AMHC. Among variables implicated in cerebral hemodynamics regulation (PETCO₂, cardiac output, blood pressure), only cardiac index was reduced in OB (1st min) and LF-OB (0–240 sec) during recovery. This indicates that obesity does not seem to have negative effects on cerebral hemodynamics and auto-regulation after exercise for the pre-frontal area measured. As well, our results underline that post exercise cardiac functions seemed preserved in HF-OB group versus AMHC. Similarly, hematological factors and inter-individual variability in NIRS could have also influenced our results in our obese subjects during recovery. Our results agree with previous studies reporting similar cerebral hemodynamics after exercise in obese subjects versus nonobese controls (Cavuoto and Maikala 2015, 2016). Other studies have reported a reduced cerebral hemodynamics during recovery in cardiac patients (Koike et al. 2004b; Gayda et al. 2016). During recovery, cerebral arterial vasodilation must be triggered to re-increased oxygenation and perfusion (Brown et al. 2010; Davenport et al. 2012), nitric oxide (NO) being an important mediator of cerebral endothelium-dependent vasodilation.

Limitations

Our study has several limitations, including the enrolment of healthy and obese subjects recruited in a single center, hence inducing a potential recruitment bias. A majority of the participants were mainly male, and frequenting our cardiovascular prevention centre. Cerebral hemodynamics were assessed using NIRS at the left prefrontal area implicating a very limited spatial resolution and a relatively superficial brain tissue measurement (light penetration ≈ 2.25 cm)(Gayda et al. 2016). Therefore, our results may differ from other more invasive and global measurement of cerebral hemodynamics (ex: catheters, transcranial Doppler or NIRS with more extensive brain coverage) or from other brain regions. Finally, cerebral NIRS signals can be influenced by extracranial tissue skin blood flow during exercise (Miyazawa et al. 2013). To limit this influence, the room temperature was standardized (thermo neutral environment: 20°C) and we have used a more important interoptode distance (4.5 cm) to allow deeper light penetration into intracranial tissues (Germon et al. 1999; Gayda et al. 2016).

Conclusion

The main findings of this study were: (1) Obese subjects groups (OB, LF-OB, HF-OB) have a similar cerebral vaso-reactivity by CO₂ (PETCO₂) and cerebral hemodynamics (COP) but higher systolic blood pressure during exercise versus AMHC. (2) During recovery, obese subjects groups (OB, LF-OB, HF-OB) have a similar cerebral hemodynamics (ROPR) versus AMHC. (3) During exercise and recovery, low-fit obese (LF-OB) have a lower cardiac function as compared to AMHC. (4) During exercise and recovery, high-fit obese (HF-OB) have a similar cardiac function versus AMHC. Our study suggests that a higher aerobic fitness in obese subjects might have a protective effect on cardiac and pulmonary function during exercise and recovery. In perspective, future studies with...
other methods of cardiac and cerebral hemodynamics measurement (such as: echocardiography and transcranial Doppler) would be required to confirm our results in obese populations with different levels of fitness and/or cardiovascular risk factors.

**Conflict of Interest**

None declared.

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