Ketone Body Infusion With 3-Hydroxybutyrate Reduces Myocardial Glucose Uptake and Increases Blood Flow in Humans: A Positron Emission Tomography Study

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Background—High levels of ketone bodies are associated with improved survival as observed with regular exercise, caloric restriction, and—most recently—treatment with sodium–glucose linked transporter 2 inhibitor antidiabetic drugs. In heart failure, indices of ketone body metabolism are upregulated, which may improve energy efficiency and increase blood flow in skeletal muscle and the kidneys. Nevertheless, it is uncertain how ketone bodies affect myocardial glucose uptake and blood flow in humans. Our study was therefore designed to test whether ketone body administration in humans reduces myocardial glucose uptake (MGU) and increases myocardial blood flow.

Methods and Results—Eight healthy subjects, median aged 60 were randomly studied twice: (1) During 390 minutes infusion of Na-3-hydroxybutyrate (KETONE) or (2) during 390 minutes infusion of saline (SALINE), together with a concomitant low-dose hyperinsulinemic–euglycemic clamp to inhibit endogenous ketogenesis. Myocardial blood flow was measured by 15O-H2O positron emission tomography/computed tomography, myocardial fatty acid metabolism by 11C-palmitate positron emission tomography/computed tomography and MGU by 18F-fluorodeoxyglucose positron emission tomography/computed tomography. Similar euglycemia, hyperinsulinemia, and suppressed free fatty acids levels were recorded on both study days; Na-3-hydroxybutyrate infusion increased circulating Na-3-hydroxybutyrate levels from zero to 3.8 ± 0.5 mmol/L. MGU was halved by hyperketonemia (MGU [nmol/g per minute]: 304 ± 97 [SALINE] versus 156 ± 62 [KETONE], P<0.01), whereas no effects were observed on palmitate uptake oxidation or esterification. Hyperketonemia increased heart rate by ≈25% and myocardial blood flow by 75%.

Conclusions—Ketone bodies displace MGU and increase myocardial blood flow in healthy humans; these novel observations suggest that ketone bodies are important cardiac fuels and vasodilators, which may have therapeutic potentials. (J Am Heart Assoc. 2017;6:e005066. DOI: 10.1161/JAHA.116.005066.)

Key Words: 11C-palmitate • 18F-fluorodeoxyglucose • cardiac metabolism • hyperketonemia • myocardial glucose uptake • myocardial perfusion • nuclear medicine • positron emission tomography/computed tomography

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parked by the recent report of a 40% reduction in cardiovascular mortality in diabetic patients treated with sodium–glucose linked transporter 2 (SGLT-2) inhibitors and the findings of upregulated ketone metabolism in heart failure, much scientific interest has lately focused on the potential role of ketone bodies, such as 3-hydroxybutyrate (3-OHB), as life-prolonging cardioprotective fuel substrates.1,2

During metabolic stress conditions, such as exercise, fasting, and severe acute illness, hepatic ketone body formation (ketogenesis) is stimulated by high levels of glucagon and free fatty acids (FFAs) and low levels of insulin in the portal bed; under such conditions, concentrations of the major ketone body, 3-OHB, may rise from close to zero to above 5 mmol/L and ketone bodies become an important fuel source. Since most tissues extract ketone bodies in proportion to their delivery,3 hyperketonemia results in a glycolysis-independent pool of acetyl-CoA and ultimately energy in the form of ATP. Oxidation of ketone bodies yields more ATP per mole of oxygen consumed than does glucose,4 and ketone body oxidation does not result in uncoupling in the mitochondrial membrane, which is a byproduct of FFA oxidation.5,6 Ketone bodies may therefore
spare hypoxic tissue. As potential results, ketone bodies are neuroprotective, induce a negative correlation between uptake of glucose and ketone in the heart has been reported, but there is still a lack of studies examining how isolated manipulation of ketone body levels affect myocardial substrate utilization and blood flow in humans. This is most likely because of the relative inaccessibility of the heart and the invasive nature of cardiac catheterization and tissue biopsy techniques. Moreover, the use of labeled ketone body tracers to directly measure rates of disappearance is inherently problematic because of unpredictable loss of label by rapid isotopic exchange in the acetyl-acetoacetyl CoA pool. Given these limitations, we examined alterations of myocardial uptake of glucose and FFA to explore the effects of myocardial ketone body exposure. Ketone bodies suppress lipolysis and ketogenesis, and we used a low-dose hyperinsulinemic clamp to control these metabolic pathways.

Our study was designed as a randomized cross-over trial in which either ketone bodies or a saline solution was infused under controlled metabolic conditions to test whether hyperketonemia would result in significantly suppressed myocardial glucose uptake and increased myocardial blood flow.

### Research Design and Methods

#### Study Participants

Eight healthy subjects (3 women) median age 60 (range 50–68) and median body mass index 25.5 (range 21.5–34.6) were recruited and completed the study. All subjects were screened for inclusion in the weeks preceding the studies. Screening included demographic data, clinical history, medical examination, heart rate, and blood pressure. Two additional subjects were originally included (1 woman, 1 man) but withdrew because of claustrophobia during the scans.

The study protocol was performed in accordance with the Declaration of Helsinki and was approved by the local institutional review board (Central Denmark Committee on Health Research [no. 1-10-72-104-14]). All subjects signed a written informed consent before entering the study.

#### Study Protocol

The study was a single-blinded, randomized cross-over study where subjects were studied under identical euglycemic clamp conditions and with identical positron emission tomography (PET) scan procedures. Study days differed in intervention, which was assigned in a random order. Study day A was a placebo study day where saline (0.9%) was infused (SALINE), whereas study day B included an infusion of 7.5% w/v Na-3-β-hydroxy-butyrate (3-OHB) (KETONE) (Figure 1).

All subjects fasted overnight for 10 hours before the study days. At t = −30 minutes, 2 catheters were inserted: the first in an antecubital vein used for infusions and the
second in a dorsal heated hand vein used for arterialized blood sampling. At \( t=0 \) minute, a continuous infusion of insulin (0.3 mU/kg per minute [Humulin, Eli Lilly, US]) and glucose (200 g/L [Fresenius Kabi]) was initiated with the glucose infusion rate continually adjusted to maintain euglycemia (5 mmol/L). On study day A, a continuous infusion of saline (0.9%) was initiated at \( t=0 \) minutes, whereas a continuous infusion of OHB (0.18 g/kg per hour) was initiated at \( t=0 \) on study day B. All infusions were maintained throughout the study days and were discontinued at \( t=390 \) minutes when all PET scans had been completed. PET scans were performed at \( t=180 \) minutes (\(^{15}\text{O-H}_2\text{O} \), \( t=210 \) minutes (\(^{11}\text{C-palmitate} \)), and at \( t=330 \) minutes (\(^{18}\text{F-fluorodeoxyglucose [FDG]} \)). Blood samples were drawn at \( t=0 \), 60, 120, 180, 240, 300, 360, and 390 minutes for analysis of FFAs and insulin and every 15 minutes for analysis of \( \text{p-glucose} \) levels. Lactate levels were measured at \( t=120, 240, \) and 390 minutes. Blood pressure and heart rate were measured every hour through the study day.

### Blood Samples

All blood samples excluding glucose were stored at \(-20^\circ\text{C} \) and analyzed in the same assay after all subjects had completed both study days. FFAs were quantified using the in vitro enzymatic colorimetric method assay NEFA-HR(2) (Wako Chemicals GmbH, Germany), glucose and lactate concentrations were measured using a YSI 2300 model STAT plus (YSI Incorporated, Netherlands), and insulin was measured by ELISA. Serum concentrations of 3-OHB were measured using hydrophilic interaction liquid chromatography tandem mass spectrometry (HILIC-MS/MS).24

### PET Scan Protocols

PET/CT scans were conducted using a Siemens Biograph 64 PET/CT (Siemens, Erlangen, Germany). Injections of radioisotopes were done in the antecubital catheter used for infusions. For arterial activity samplings (\(^{11}\text{C-palmitate} \)), a catheter was inserted in the contralateral radial artery at \( t=120 \) minutes. Patients were placed with the heart in the field of view and a low-dose CT scan was obtained for attenuation and anatomic localization purposes. At \( t=180 \) minutes, 400 MBq \(^{15}\text{O-H}_2\text{O} \) was administered and simultaneously, a 6-minute list mode PET scan was begun with the following time-frame sequence: \( 1 \times 10, 8 \times 5, 4 \times 20, 2 \times 15, 3 \times 20, 2 \times 30, \) and \( 2 \times 60 \) s. Images were reconstructed using a 3-dimensional (D) iterative algorithm (3 iterations, 21 subsets, 5-mm Gaussian postfilter), applying all appropriate corrections for normalization, dead time, random coincidences, scatter, and attenuation.

The \(^{11}\text{C-palmitate} \) scan was initiated at \( t=210 \) minutes allowing for sufficient decay of residual \(^{15}\text{O-H}_2\text{O} \) activity. Thus, \(^{11}\text{C-palmitate} \) was injected as a bolus (283±65 MBq [SALINE] or 274±62 MBq [KETONE]) and a 50-minute list mode scan (frame structure \( 6 \times 5, 6 \times 10, 3 \times 20, 5 \times 30, 5 \times 60, 8 \times 150, 4 \times 300 \) s) was performed with 37 manual blood samples taken during the scan. Plasma as well as whole-blood activity were measured in a well counter (Cobra II; Packard Instruments Co.) cross-calibrated to the tomograph. Data were reconstructed using a 3D iterative algorithm (3 iterations, 21 subsets, 5-mm Gaussian postfilter). Blood and dynamic PET data were decay corrected to scan start. After completion of the \(^{11}\text{C-palmitate} \) scan, subjects were moved to a bed in the adjoining room to await the final scan.

At \( t=315 \) minutes, a second low-dose CT scan was acquired using the same protocol as previously described. At \( t=330 \) minutes, \( \approx 200 \) MBq \(^{18}\text{F-FDG} \) was administered and a 50-minute list mode scan (frame structure \( 1 \times 10, 8 \times 5, 4 \times 10, 3 \times 20, 5 \times 30, 5 \times 60, 4 \times 150, 4 \times 300, \) and \( 1 \times 600 \) s) was performed using 3D iterative reconstruction (3 subsets, 21 iterations, 4-mm Gaussian postfilter). Voxel size for all 3 scans was \( 4 \times 4 \times 4 \) mm.

### Tracer Kinetics

Perfusion: Myocardial blood flow (MBF), expressed in mL/g per minute, was calculated using Cardiac VUer.25 In brief, the arterial and venous blood pool were segmented automatically and used to extract the arterial input function, which was then used to generate parametric images of MBF. Then, these parametric images were used for reorientation to short-axis images on which the left ventricle was then defined according to the recommendations of the American Heart Association. MBF is reported for the left ventricle as a whole, but also for the 3 vascular territories (left anterior descending, left circumflex, and right coronary).

### Myocardial fatty acid metabolism

Using in-house developed software, myocardial fatty acid metabolism was analyzed using a 3-tissue compartment model in which 3 rate constants need to be fitted. In this model, the efflux \(^{11}\text{CO}_2 \) rate is fixed to the oxidation rate and a slow esterification compartment is included. Macroparameters myocardial fatty acid oxidation (MFAO), myocardial fatty acid esterification (MFAE), and myocardial fatty acid uptake (MFAU) were defined according to the suggestions by Bergmann et al26:

\[
\text{MFAE} = C_{\text{NEFA}} \frac{k_{p1}k_{12}}{k_{1p} + k_{12} + k_{13}}
\]
MFAO = \frac{C_{NEFA} k_{p1} k_{13}}{k_{tp} + k_{12} + k_{13}}

MFAU = MFAE + MFAO

Segmentation of the blood pool, reorientation of the images, and definition of the left ventricle was performed in a way similar to the analysis of the perfusion scans. For the all calculations and parametric images, the input function was corrected for \(^{11}\)C-metabolites using arterial blood samples as validated by Guiducci et al.\(^{27}\)

Myocardial glucose uptake

Myocardial glucose uptake (MGU) rate from the dynamic \(^{18}\)F-FDG scan was estimated by Patlak analysis\(^{28}\) using Cardiac VUer. Irreversible uptake rate, \(K_i\), was first estimated from the relation

\[
\frac{C_i(t)}{C_p(t)} = \frac{K_i}{C_p(t)} + V_d
\]

where \(C_i\) is the myocardial \(^{18}\)F-FDG radioactivity and \(C_p\) is the plasma \(^{18}\)F-FDG radioactivity at time \(t\). Plots of \(C_i(t)/C_p(t)\) versus \(\int C_p dt/C_p(t)\) were fitted to straight lines by conventional least-squares methods and the slopes of the best fits were taken as estimates of \(K_i\). Absolute myocardial glucose uptake rate (nmol/g per minute) was calculated using the equation

\[
MGU = pGlc \frac{K_i}{LC}
\]

where \(pGlc\) is plasma glucose concentration and \(LC\) is the lumped constant. The lumped constant was assumed not to differ between visits (as demonstrated by previous work performed during similar study conditions)\(^{29}\) and was therefore fixed at 1.

Statistics

Normal distribution was assessed by inspection of QQ-plots and data were ln-transformed when appropriate. Curves are presented as means±SE, whereas all other data involving group comparisons are presented as means±SD. Statistical comparisons between study days were performed by a paired \(t\) test or a mixed-model repeated-measures ANOVA when appropriate (time series). The mixed model was a 2-way ANOVA with time and treatment as factor variables and the time versus treatment interaction as the term of interest. The level of significance was set at \(P<0.05\). All statistical analyses were performed using SPSS version 21.

Results

Hemodynamics, MBF, and pH

Blood pressure and heart rate during the study days are presented in Figure 2. On the SALINE study day, blood pressure and heart rate remained stable, whereas heart rate increased \(\approx 25\%\) from 62±13 to 78±8 mm Hg during the KETONE study day (repeated measurements treatment×time, \(P<0.001\)). We observed a uniform 75\% increase in resting MBF in all vascular territories (at \(t=180\) minutes) as shown in Table 1. Arterial pH was measured in a subset of patients (\(n=4\)) and increased from 7.42 (range 7.41–7.43) to 7.50 (range 7.46–7.52), \(P<0.01\).

Hormones and Metabolites

As seen in Figure 3A, circulating \(OHB\) was below the detection threshold during the SALINE study day. 3-OHB

Figure 2. Hemodynamics. Systolic (treatment×time, \(P=0.54\)) blood pressure was comparable on the 2 study days (A), whereas heart diastolic blood pressure (treatment×time, \(P<0.001\)) decreased and heart rate (treatment×time, \(P<0.001\)) increased significantly during the KETONES study day (B). BPM indicates beats per minute.
increased rapidly during the KETONE study day, reaching mean values $\approx 3$ mmol/L at $t=180$ minutes with a further increase to a $\approx 4$ mmol/L plateau phase at $t=300$ minutes. FFA levels decreased rapidly during both study days, reaching an almost complete suppression at $t=120$ minutes. A tendency towards lower levels of FFAs was observed during the KETONE day even though this did not reach statistical significance (Figure 3B). Average circulating lactate levels were increased $\approx 35\%$ by the ketone infusion (Table 2).

The hyperinsulinemic–euglycemic clamp increased insulin levels by a factor of 3 with no difference in mean levels from $t=180$ to 390 (Table 2). A dynamic difference was evident on the KETONE study day, as insulin levels increased more in the early stages while a late-onset decrease was observed from $t=120$ minutes.

Several ex vivo studies have established that cardiomyocytes oxidize ketone bodies at the expense of glucose, presumably by inhibition of pyruvate dehydrogenase or possibly by sequestration of coenzyme A impairing oxidative glucose flux at the entry to the tricarboxylic acid cycle. The ex vivo and animal studies of cardiomyocytes have not previously been extended to a human setting. However, there is substantial indirect evidence from human studies to support the notion. Ferrannini et al investigated cardiac substrate metabolism across the heart in 16-hour-fasted humans and reported that both fatty acids and ketone bodies constituted a significant proportion of cardiac fuel during basal conditions. The contribution from lipid fuels was almost completely abolished during hyperinsulinemia. Although the study indicates that the heart utilizes and oxidizes ketone bodies after fasting, it did not establish to which extent utilization of 3-OHB, glucose, and FFA was affected by insulin, high levels of FFA, or intrinsic to the moderately high levels of 3-OHB per se.

### Discussion

In line with our preliminary hypothesis, we observed a halving of myocardial glucose uptake during experimental hyperketonemia, supporting the notion that the human heart utilizes and oxidizes ketone bodies at the expense of glucose in spite of ongoing insulin stimulation. Hyperketonemia did not affect myocardial fatty acid transport or oxidative capacity in a metabolic setting of very low circulating FFAs, but increased heart rate 25% and myocardial blood flow 75%.

### Myocardial Glucose Uptake Is Halved by Hyperketonemia

Several ex vivo studies have established that cardiomyocytes oxidize ketone bodies at the expense of glucose, presumably by inhibition of pyruvate dehydrogenase or possibly by sequestration of coenzyme A impairing oxidative glucose flux at the entry to the tricarboxylic acid cycle. The ex vivo and animal studies of cardiomyocytes have not previously been extended to a human setting. However, there is substantial indirect evidence from human studies to support the notion. Ferrannini et al investigated cardiac substrate metabolism across the heart in 16-hour-fasted humans and reported that both fatty acids and ketone bodies constituted a significant proportion of cardiac fuel during basal conditions. The contribution from lipid fuels was almost completely abolished during hyperinsulinemia. Although the study indicates that the heart utilizes and oxidizes ketone bodies after fasting, it did not establish to which extent utilization of 3-OHB, glucose, and FFA was affected by insulin, high levels of FFA, or intrinsic to the moderately high levels of 3-OHB per se. By contrast, our data clearly show that high levels of 3-OHB displace glucose utilization by the myocardium in the presence of well-controlled hyperinsulinemia and suppressed FFA levels. It is of interest that the marked reduction in myocardial glucose uptake occurred in the presence of a 75% increase in myocardial blood flow. If anything, the increased myocardial blood flow would be expected to increase myocardial glucose uptake, which correlates with tissue perfusion in striated muscle.

### Myocardial 18F-FDG Uptake

Experimental hyperketonemia roughly halved myocardial glucose uptake ($304\pm 97–155\pm 61$ nmol/g per minute [$P=0.03$]) exclusively because of a reduction in relative uptake rate (Ki) (Figure 5). No correlation was observed between plateau 3-OHB levels obtained and the reduction in MGU.
During a hyperinsulinemic–euglycemic clamp, the heart derives most of its ATP from oxidation of glucose or lactate\textsuperscript{36} and only a small proportion from lipids. This was also evident in this study, where glucose uptake during the control study day (in \textmu{}mol/g heart tissue/min) was 30-fold higher than fatty acid uptake as opposed to a ratio of roughly 1 observed in studies under normal fasting conditions (see eg,\textsuperscript{37}). It is therefore reasonable to assume that a halving of MGU in absolute terms during the ketone body infusion implies that a significant proportion of the heart’s energy needs was met by ketone body oxidation, although some of the reduction in MGU observed can also be ascribed to the increased lactate levels. On the other hand, increased lactate levels could also be a consequence of either reduced entrance of glycolytic end products in the tricarboxylic acid cycle because of substrate competition from ketones\textsuperscript{22} or limited transfer of reducing equivalents through the malate–aspartate shuttle leading to reduced metabolism of glucose and lactate.\textsuperscript{38,39}

Table 2. Average Hormone and Metabolite Concentrations (t=180–390 Minutes)

<table>
<thead>
<tr>
<th>Hormones and Metabolites</th>
<th>SALINE</th>
<th>KETONE</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-OHB, mmol/L</td>
<td>0.05 (0.00)</td>
<td>3.78 (0.47)</td>
<td>&lt;0.00001</td>
</tr>
<tr>
<td>FFA, mmol/L</td>
<td>0.06 (0.05)</td>
<td>0.04 (0.03)</td>
<td>0.14</td>
</tr>
<tr>
<td>Insulin, pmol/L</td>
<td>176 (45)</td>
<td>178 (63)</td>
<td>0.89</td>
</tr>
<tr>
<td>Lactate, pmol/L</td>
<td>1.05 (0.14)</td>
<td>1.44 (0.35)</td>
<td>0.02</td>
</tr>
<tr>
<td>Glucose, mmol/L</td>
<td>5.2 (0.1)</td>
<td>5.1 (0.2)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

\( N=8 \), mean values (SD). FFA indicates free fatty acids; OHB, hydroxybutyrate.

During a hyperinsulinemic–euglycemic clamp, the heart derives most of its ATP from oxidation of glucose or lactate\textsuperscript{36} and only a small proportion from lipids. This was also evident in this study, where glucose uptake during the control study day (in \textmu{}mol/g heart tissue/min) was 30-fold higher than fatty acid uptake as opposed to a ratio of roughly 1 observed in studies under normal fasting conditions (see eg,\textsuperscript{37}). It is therefore reasonable to assume that a halving of MGU in absolute terms during the ketone body infusion implies that a significant proportion of the heart’s energy needs was met by ketone body oxidation, although some of the reduction in MGU observed can also be ascribed to the increased lactate levels. On the other hand, increased lactate levels could also be a consequence of either reduced entrance of glycolytic end products in the tricarboxylic acid cycle because of substrate competition from ketones\textsuperscript{22} or limited transfer of reducing equivalents through the malate–aspartate shuttle leading to reduced metabolism of glucose and lactate.\textsuperscript{38,39}
Myocardial Fatty Acid Kinetics Is Unaltered by Hyperketonemia in a Setting of Depressed Circulating FFAs

In theory, ketone bodies can affect fatty acid metabolism either at the level of entry into the cardiomyocytes or at the mitochondrial level. At the level of entry, active transport of fatty acids via CD36 may account for up to 60% of fatty acid uptake into the cardiomyocytes while passive diffusion or transport via other carriers account for the rest. At the mitochondrial level, fatty acyl-CoA is transported into the mitochondria for oxidation by carnitine palmitoyltransferase I. Carnitine palmitoyltransferase I activity has long been considered to be inhibited by malonyl-CoA, which increases with intracellular energy substrate levels, but this concept of a simple substrate feedback loop has now been challenged. In line with this, Stanley et al. studied myocardial fatty acid oxidation both during infusion of a lipid emulsion and during infusion of lipids plus ketone bodies in pigs and found a significant decrease in fatty acid oxidation without affecting levels of malonyl-CoA, acetyl-CoA, or acetyl-CoA decarboxylase. In that study, ketone bodies appeared to inhibit fatty acid oxidation at the level of entry into the cell rather than via inhibition of carnitine palmitoyltransferase I. In the present study, fatty acid transport capacity into the cells was not affected by hyperketonemia as assessed by the similar MFAU rates during the saline and β-hydroxybutyrate infusions. Ketone bodies therefore do not appear to modulate CD36 transport directly. The previously observed reduced myocardial fatty acid uptake during hyperketonemia is more likely because of reduced passive diffusion of fatty acids over the sarcolemmal membrane. However, the intact cellular membrane fatty acid transport capacity in the setting of hyperketonemia was measured during almost completely suppressed levels of circulating FFAs. For comparison, myocardial fatty acid oxidation during modest hyperketonemia (∼1 mmol/L) has been studied by others using 11C-palmitate PET in human subjects and in dogs. In that study, fatty acid oxidation was significantly decreased by hyperketonemia, but this occurred in the presence of 50% reduced circulating FFAs. Most likely, their findings reflected a decreased supply of substrate rather than a direct inhibitory effect of ketone bodies on the ability of the myocardium to oxidize fatty acids.

In summary, our results from the kinetic analysis of myocardial 11C-palmitate metabolism showed no effect of hyperketonemia on relative or absolute fatty acid uptake and oxidation rates, while relative esterification rates increased, compatible with the notion that the inhibitory effect of ketone bodies on myocardial fatty acid uptake is a consequence of substrate competition.

Myocardial Perfusion and Heart Rate Is Increased by Hyperketonemia

One of the more striking results of this study was the 75% increase in myocardial blood flow observed during hyperketonemia. There may be several explanations for this.

First, it seems obvious to relate this to the concomitant 25% increase in heart rate. Numerous studies have shown a linear relationship between resting heart rate and MBF on a population level (reviewed by). However, on the level of the individual, heart rate and myocardial perfusion do not necessarily increase in tandem in the 60 to 80 beats/min range, because any increase in heart rate shortens the duration of the diastole whereby coronary blood flow is inhibited. Only when heart rate is increased to such an extent that metabolic factors become more prominent, does significant vasodilation occur. The relationship between increasing heart rate and myocardial blood flow is therefore sigmoidal.

The modest average ketone-induced increase in heart rate of 18 beats/min observed in this study should therefore not translate into a 75% increase in MBF.

Second, it is possible that increased blood pH caused by infusion of a β-hydroxybutyrate salt might affect myocardial blood flow. Thus, acutely elevated levels of ketone bodies result in a loss of potassium from the kidney tubules as the cation acts as a partner to the negatively charged β-hydroxybutyrate. Decreasing levels of potassium in the blood spark an exchange of H+ from the blood with intracellular potassium, and the resulting decrease in blood...
H+ constitutes a metabolic alkalosis. In line with this, 4 patients in whom we measured blood pH during the ketone body infusion had pH values \( \geq 7.5 \) and potassium just above 3 mmol/L. Since a discrete 0.08 increase in blood pH has been shown to increase myocardial blood flow up to 50% in mongrel dogs,\(^47\) it is conceivable that the mild metabolic alkalosis our subjects suffered during the ketone body infusion may contribute to the increased MBF.

Third, hyperketonemia seems to increase perfusion or blood flow in other tissues independently of changes in pH or heart rate. Forearm blood increases 15% in human volunteers during infusion of \( \beta \)-hydroxybutyrate\(^48\) in amounts sufficient to obtain plateau values of as little as 0.5 mmol/L, a fraction of what we observed in this study. More interesting from a physiological point of view are the numerous studies that report a stimulatory effect of ketone bodies on cerebral blood flow. Hasselbalch et al observed a 39% increase in cerebral blood flow in human volunteers during short-term infusion of \( \beta \)-hydroxybutyrate,\(^20\) a finding that could not be ascribed to either blood glucose levels or pH, perhaps reflecting that ketone bodies act directly on the endothelium to produce vasodilation. Another study reported that 3-OHB infusion increased renal plasma flow measured with hippurate by 20% in humans,\(^21\) thus supporting the concept of general vasodilatory effects of ketone bodies.

As outlined above, several factors may combine to explain how infusion of ketone bodies results in a significantly increased MBF, whereas the mechanisms leading to increased

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**Table 3. Mean FMAO, MFAE, MFAU (SD) (SD)**

<table>
<thead>
<tr>
<th>Transfer Rate</th>
<th>(^{11}C)-Palmitate Relative Transfer Rates</th>
<th>(^{18}F)-FDG relative uptake</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SALINE</td>
<td>0.10 (0.02)</td>
<td>0.10 (0.05)</td>
<td>0.84</td>
</tr>
<tr>
<td>KETONE</td>
<td>0.06 (0.02)</td>
<td>0.08 (0.03)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MFAU</td>
<td>0.16 (0.03)</td>
<td>0.18 (0.06)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

MFAE indicates myocardial fatty acid esterification; MFAO, myocardial fatty acid oxidation; MFAU, myocardial fatty acid uptake.

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**Figure 5.** Myocardial \(^{18}F\)-FDG uptake. Summed images (=10–50 minutes) from a representative subject are presented in the left panel. Infusion of OHB significantly decreased \(^{18}F\)-FDG uptake in all subjects, resulting in significantly lower relative uptake rates (Ki) when compared with the SALINE study day (A). Since blood glucose levels were clamped at \( \approx 5 \) mmol/L, the resulting absolute MGU was roughly halved (B). N=8, error bars are SD. FDG indicates fluorodeoxyglucose; MGU, myocardial glucose uptake; OHB, hydroxybutyrate; SUV, standardized uptake value.
heart rate are more uncertain. If anything, \(\beta\)-hydroxybutyrate decreases sympathetic outflow in HEK293 cells by antagonizing the G-Protein Coupled Receptor 41,49 which in theory should translate into a decreased heart rate. Also, the modest sodium loading associated with infusion of the ketone body salt should contribute to a lowering of heart rate rather than an increment.50 On the other hand, in studies in athletes fed a ketogenic diet, resting heart rate has been demonstrated to be slightly increased51 despite comparable levels of norepinephrine. Unfortunately, measurements of heart rate have not been reported in previous studies using exogenous ketone body infusions to study the effects of hyperketonemia on diverse segments of physiology and pathophysiology.20,52,53

It should be noted that many patients with the metabolic syndrome and type 2 diabetes have endothelial dysfunction and that increased myocardial perfusion in these patients may have beneficial effects.54 It thus remains a possibility that the sharp reduction in cardiovascular mortality following treatment with SGLT-2 inhibitors in clinical trials15 could be caused by a combination of increased myocardial blood flow and increased myocardial oxygen efficiency driven by high levels of ketone bodies.

**Experimental Design**

In vivo studies of substrate metabolism are inherently challenging. For instance, ketone bodies bind to nicotinic acid receptors55 and inhibit peripheral lipolysis and reduce circulating FFAs. Reduced levels of FFAs simultaneously increase insulin sensitivity, lower insulin levels, and reduce blood glucose56 and endogenous ketogenesis. As a result, any intervention involving ketone bodies is bound to affect the most prominent circulating energy substrates as well as their regulatory hormones.

This study was designed in an attempt to control these particular challenges: The modest (0.3 mIE/kg per minute) hyperinsulinemic–euglycemic clamp ensured comparable insulin sensitivity, lower insulin levels, and reduce blood glucose56 and endogenous ketogenesis. As a result, any intervention involving ketone bodies is bound to affect the most prominent circulating energy substrates as well as their regulatory hormones.

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Figure 6. Myocardial fatty acid metabolism. A, Summed images (t=10–50 minutes) from a representative subject are presented in the left panel. There was no visible difference in accumulated \(^{11}\text{C}\)-palmitate in most subjects. B, Myocardial \(^{11}\text{C}\)-palmitate metabolism. The 3-tissue compartment model has 3 free parameters (black arrows) and 3 fixed parameters (dotted arrows). C, No differences were observed in myocardial fatty acid uptake, esterification, or oxidation (black bar: Saline, white bar: Ketone). N=7, error bars are SD. MFAE indicates myocardial fatty acid esterification; MFAO, myocardial fatty acid oxidation; MFAU, myocardial fatty acid uptake; SUV, standardized uptake value.
differed significantly in terms of ketone body levels. Metabolic conditions with ample supplies of glucose, high insulin, and suppressed circulating fatty acid levels most closely mimic the fed state. It can be argued that ketone body levels only rarely are increased during feeding, but as previously mentioned, this may be the case in patients with heart failure or in diabetic patients treated with SGLT-2 inhibitors. Furthermore, a very recent study has shown that co-administration of glucose and 3-hydroxybutyrate esters, creating a similar metabolically favorable scenario with high insulin levels and suppressed FFAs, improves exercise performance in humans.

Some major drawbacks to the study design should be mentioned. By design, FFA levels were clamped at comparable low levels on both study days, which does not reflect the classical hyperketonemic setting of increased circulating FFAs as seen during fasting, metabolic stress, or exercise. It is possible that this may have influenced our estimates of 11C-palmitate kinetics. Also, blood ketone body levels were experimentally rapidly elevated and sustained for only 6.5 hours, which precludes us from studying the metabolic effects of putative negative feedback mechanisms on key ketolytic enzymes in the heart. The proof-of-concept nature of the study design called for a significant increase in circulating ketone bodies in order to obtain robust primary end point results (PET-based MGU). The ketone body concentrations obtained in our volunteers are therefore much greater than what could be expected from treatment with SGLT-2 inhibitors or even several days of fasting. Finally, our study design did not include direct measurements of cardiac ketone body uptake, and we can therefore only conclude by inference that the reduced myocardial glucose uptake was replaced by ketone bodies.

Conclusion

We used dynamic 11C-palmitate, 15O-H2O, and 18F-FDG PET/CT to demonstrate for the first time in humans that hyperketonemia in the setting of concomitant hyperinsulinemia significantly reduces myocardial glucose uptake and increases myocardial blood flow. The striking ability of 3-OHB to replace myocardial glucose utilization and to increase myocardial blood flow warrants further investigations of the potential of ketone bodies to increase myocardial oxygen efficiency (eg, during exercise and in patients with cardiac disease), in line with the marked reduction of cardiovascular mortality in patients rendered hyperketonemic by treatment with SGLT-2 inhibitors.

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Disclosures

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