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Monitoring creatine and phosphocreatine by $^{13}$C MR spectroscopic imaging during and after $^{13}$C4 creatine loading: a feasibility study

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Abstract Creatine (Cr) supplementation to enhance muscle performance shows variable responses among individuals and different muscles. Direct monitoring of the supplied Cr in muscles would address these differences. In this feasibility study, we introduce in vivo 3D $^{13}$C MR spectroscopic imaging (MRSI) of the leg with oral ingestion of $^{13}$C4-creatine to observe simultaneously Cr and phosphocreatine (PCr) for assessing Cr uptake, turnover, and the ratio PCr over total Cr (TCr) in individual muscles. $^{13}$C MRSI was performed of five muscles in the posterior thigh in seven subjects (two males and two females of ~20 years, one 82-year-old male, and two neuromuscular patients) with a $^1$H/$^{13}$C coil in a 3T MR system before, during and after intake of 15 % $^{13}$C4-enriched Cr. Subjects ingested 20 g Cr/day for 4 days in four 5 g doses at equal time intervals. The PCr/TCr did not vary significantly during supplementation and was similar for all subjects and investigated muscles (average 0.71 ± 0.07), except for the adductor magnus (0.64 ± 0.03). The average Cr turnover rate, assessed in male muscles, was 2.1 ± 0.7 %/day. The linear uptake rates of Cr were variable between muscles, although not significantly different. This assessment was possible in all investigated muscles of young male volunteers, but less so in muscles of the other subjects due to lower signal-to-noise ratio. Improvements for future studies are discussed. In vivo $^{13}$C MRSI after $^{13}$C–Cr ingestion is demonstrated for longitudinal studies of Cr uptake, turnover, and PCr/TCr ratios of individual muscles in one exam.

Keywords Creatine · MR spectroscopy · $^{13}$C · Human muscle

Introduction

Creatine (Cr) occurs in fish and meat and is endogenously produced in the liver and kidneys (Guthmiller et al. 1994). It is taken up from blood vessels into tissues with high energy demands such as muscle and brain (Wyss and Kadhurah-Daouk 2000). This uptake is facilitated by a creatine transporter protein (CrT), which transports the compound together with sodium into the cell against a Cr concentration gradient (Guerrero-Ontiveros and Wallimann 1998). Inside the cell, Cr is reversibly phosphorylated to phosphocreatine (PCr) in the creatine kinase (CK) reaction. This Cr–PCr system plays a key role in energy metabolism as a temporal energy buffer and by facilitating substrate diffusion (Meyer et al. 1984). A spontaneous reaction irreversibly degrades both Cr and PCr into creatinine, which is excreted via the kidneys (Wallimann et al. 2011; Hoberman et al. 1948). Because of low PCr levels in some dystrophic muscles (Kemp et al. 1993) and potential cellular protective effects (Pulido et al. 1998), Cr supplementation has been proposed as treatment for several neuromuscular disorders (Kley et al. 2013). Cr is also recognized as an effective nutritional supplement in other diseases and in sports.
(Wyss and Schulze 2002; Gualano et al. 2012; Kley et al. 2013).

However, selection of an effective Cr loading protocol is hampered by a wide variation in responsiveness between individuals (Harris et al. 1992; Greenhaff et al. 1994). This may be due to various factors determining Cr uptake, such as intracellular Cr concentration, hormone status, and fiber type composition (Mesa et al. 2002; Snow and Murphy 2003). Moreover, the contribution of each factor may vary between different muscles and may change with age or due to disease (Coggan et al. 1992; Kreis et al. 1999; Dubowitz and Sewry 2007; McCall and Persky 2007). Therefore, an in vivo method to directly monitor the supplied Cr in individual muscles would be desirable to help to understand and optimize Cr loading.

Magnetic resonance spectroscopy (MRS) has the unique capability to measure Cr and PCr levels in human tissues non-invasively. With proton (1H) MRS, the total amount of Cr (TCr) in muscles can be observed, and with phosphorus (31P) MRS, it is possible to monitor PCr (De Graaf 2007). Both 1H and 31P MRS have been used in studies of TCr and PCr levels in skeletal muscle after Cr supplementation and revealed differential Cr increases ranging from about 5 % in the gastrocnemius to about 23 % in the quadriceps femoris (Vandenbergh et al. 1997; Kreis et al. 1999; Smith et al. 1998, 1999). To examine these two compounds individually in one exam are complicated as different hardware is required for each nucleus and quantitative sequential measurements are hampered by the required calibrations (Brault et al. 2007). By carbon (13C) MRS, it is possible to observe separate signals for Cr and PCr simultaneously in skeletal muscle spectra, but because of the low natural abundance of 13C in the body, this is not a very sensitive method. However, with oral ingestion of 13C-4 labeled Cr, the signal-to-noise ratio can be increased. This was used to establish the PCr/TCr ratio and Cr turnover in the calf of a single individual only employing a surface coil adjacent to the calf for localization, mainly acquiring signal from the gastrocnemius (Kan et al. 2006). Multiple spatially resolved MR spectra can be acquired with MR spectroscopic imaging (MRSI) and, therefore, allow the detection of metabolites in individual muscles (Vermathen et al. 2012). Human muscles have not been assessed yet by 13C MRSI to monitor compounds labeled with 13C spins at thermal equilibrium.

The aim of the work described in this paper was to investigate the performance of three-dimensional 13C MRSI at 3T of the posterior thigh during and after the ingestion of 13C-4 labeled Cr. In particular, we wanted to know for different muscles what the PCr/TCr ratio is and how feasible it is to measure Cr turnover and uptake, all in one examination. To test this feasibility of the method for clinical research, we examined a variety of seven volunteers representing potentially different leg muscle conditions, including two patients suffering from facioscapulohumeral muscular dystrophy (FSHD).

### Materials and methods

#### Subjects

For this feasibility study, we included four healthy young volunteers (YH), one 82-year-old male (OH), and two genetically confirmed FSHD patients. We made sure that participants had no MR contraindication (pacemaker, metal implants or claustrophobia). None of the subjects performed sports at a professional level, were vegetarian, or were taking Cr as supplement.

Participants’ demographics are listed in Table 1. Ethical approval was obtained through the institutional review board, and written informed consent was obtained from all participants.

#### Study design

Participants ingested 20 g Cr per day for 4 days in four 5 g doses (15 % 13C enriched at the guanidino carbon, 13C-4–Cr) at equally spaced intervals through the day. They were instructed to dilute the Cr in a glass of lukewarm water and to drink it along with 250 ml of standard carbohydrate solution to augment skeletal muscle Cr accumulation (Green et al. 1996).

After the first MR measurement on day 0, the participant was provided with 16 portions of the 13C-enriched Cr, and was instructed to start the Cr supplementation the next day. The full study design consisted of 12 MR measurements at day 0, 1, 2, 3, 4, 5, 7, 12 ± 1, 14 ± 1, 19 ± 2, 41 ± 3, 78 ± 3, and 105 ± 3. Day 0 was the baseline measurement, days 1–4 were during Cr supplementation, and the remaining measurements were after Cr supplementation. The measurement protocol was reduced to six MR exams representing potentially different leg muscle conditions, including two patients suffering from facioscapulohumeral muscular dystrophy (FSHD).

#### Table 1 Participants demographics

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>BMI (kg/m²)</th>
<th>Weight (kg)</th>
<th>Gender</th>
</tr>
</thead>
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<tr>
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<td>30.67</td>
<td>95</td>
</tr>
<tr>
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<td>72</td>
<td>33.46</td>
<td>90</td>
</tr>
<tr>
<td>FSHD #2</td>
<td>41</td>
<td>24.68</td>
<td>73</td>
</tr>
</tbody>
</table>

Fat fractions were similar between young healthy man and women (1.2 ± 0.3 % vs. 2.8 ± 0.8, p = 0.08 two-tailed t test)
for the older and FSHD subjects; one before Cr supplementation (day 0), two during (days 2 and 5), and three after (days 19, 41, and 78) Cr supplementation.

Blood and urine samples were taken on days 0, 3, and 7 to monitor kidney function during Cr supplementation. Venous blood was drawn directly into a K₂-EDTA vacuum tube. Tubes were centrifuged at 3000 revolutions per minute for 10 min, and subsequently, the plasma was separated from the packed red blood cells and was stored at −80 °C until analysis. Cr and 13C-4–Cr concentrations were determined with mass spectroscopy.

MR protocol

MR exams were performed on a clinical 3Tesla MRI system (Tim Trio, Siemens, Erlangen, Germany) with a 1H birdcage volume coil (diameter 25 cm) and a circularly polarized 13C half-volume coil (13 × 15 cm) inserted into the 1H coil. A fish oil capsule served as a matching landmark between the MR exams and was positioned at one-third the distance between the anterior superior iliac spine and the patella. Subjects were placed feet first supine inside the magnet bore, and the coil was placed around the right upper leg. After scout imaging, the protocol consisted of T2 multi-spin-echo imaging (T2-MRI; Kan et al. 2009) (field of view 175 × 175 mm, voxel size 0.68 × 0.68 mm repetition time (TR) 3000 ms, 16 equally spaced echo times (TE) 7.7–123.2 ms, 8 slices, slice thickness/gap 6/9 mm).

Followed by 3D, 13C MRSI with an adiabatic BIR45 excitation pulse centered at 157 ppm, which is between the resonance frequencies of Cr and PCr. The FOV was 200 × 200 × 400 mm, and the matrix size was 10 × 10 × 8, resulting in nominal voxels of 20 × 20 × 50 mm. Furthermore, Hamming-weighted k-space acquisition was applied with TR 1000 ms, bandwidth 10 kHz, vector size 1024, and 30 averages with WALTZ16 proton decoupling during acquisition.

In one subject, a T₁ measurement was performed at day 10, by acquiring 13C free induction decays (with adiabatic excitation and 150 averages) at different repetition times (TR = 0.75, 1, 2, 3, and 8 s).

Because of the 13C coil sensitivity profile only spectra from the posterior thigh muscles, more specifically, the biceps femoris (BF), semimembranosus (SM), semitendinosus (ST), adductor magnus (AM), and the gracilis (G) were collected (Fig. 1). The entire MR examination took about 1 h, including subject placement. All MRSI data sets were saved as raw files for off line processing.

Data analyses

Muscle specific fat-fractions were determined by fitting the signal of the multi-spin-echo images to a biexponential function with fixed relaxation times for fat and water as described previously (Kan et al. 2009), classifying severe fatty infiltration as a fat fraction above 80 % and minor as below 20 %.

For the 13C MRSI data, the matrix dimension was zero-filled to 16 × 16 × 8. A spatial 100 % Hamming filter was applied to the 13C MRSI k-space data before voxel selection. From every slice in the field of view of the 13C coil, one voxel was selected per muscle using the program 3DiCSI (Zhao et al. 2005). To position the voxel in the center of the muscle, grid-shifting was applied. Only voxels were selected that were completely lying within one muscle, resulting in three voxels per muscle on average. The corresponding free induction decays (FID) were exported to jMRUI 4.0 for spectral fitting (Naressi et al. 2001).

Spectral fitting

Voxels from the same muscle were summed, subsequently, unwanted lipid resonances were removed from the 13C spectra with an HLSVD filter (Pijnappel et al. 1992), and the spectra were apodized by 10 Hz. From unlocalized high SNR MR spectra, a line width ratio of 0.81 and a
frequency difference of 30 Hz between Cr (157.5 ppm) and PCr (156.6 ppm) were obtained as prior knowledge that was used in the fit of the signals to Gaussian line shapes using AMARES software (Vanhame et al. 1997). With the Cr and PCr pools in equilibrium (Brault and Terjung 2003), the summed signal intensities of Cr and PCr served as TCr. Spectral quality was assessed by comparing the TCr signal intensity to the standard deviation (SD) of the noise (defined as SD of the last 10% of the FID). Only spectra in which the TCr signal intensity was larger than the SD of the noise were included for further analysis. In addition, we excluded spectra in which the fitted line width of the $^{13}$C creatine signals was more than 50 Hz.

**Creatine uptake**

TCr amplitudes of individual muscles at days 0 till 5 were fitted to a linear function (Eq. 1) where $T_{Cr}(t)$ is the $^{13}$C signal intensity at measurement day $t$. This was only calculated for the muscles that had at least 3 measurement days with spectra that passed the quality criteria (see above). The fitted slope gives the Cr uptake rate ($k_{up}$) and the intercept the initial TCr value ($TCr_0$), both in arbitrary units (a.u.). The final uptake rate is presented as $k_{up}/TCr_0$ to give a value expressed in percentage per day. The error of the fit was treated as the standard deviation.

$$T_{Cr}(t) = k_{up} t + T_{Cr_0} \quad (1)$$

**Creatine turnover**

TCr signal intensities from day 5–105 were used to calculate the turnover rate. Cr breakdown is assumed to follow first order kinetics (Walker 1979), so TCr signal intensities were fitted to a mono-exponential function (Eq. 2), under the assumptions described in (Kan et al. 2006). The maximal $^{13}$C TCr signal intensity is $T_{Cr_{max}}$, and $k_{br}$ is the breakdown rate (% per day). The error of the fit was treated as the standard deviation. All curve fitting was done using Prism 5.0 (GraphPad Software, San Diego, CA, USA).

$$\frac{T_{Cr}(t)}{T_{Cr_0}} = \frac{(T_{Cr_{max}} - T_{Cr_0})e^{-k_{br}t}}{T_{Cr_0}} + 1 \quad (2)$$

**PCr/TCr ratio**

The PCr/TCr ratio was determined per muscle over time for every measurement point unless the Cr and PCr signals could not be resolved properly (i.e., one or both signals fitted with amplitude 0). To compare the PCr/TCr ratios between individual muscles, the PCr/TCr ratios were averaged over all these measurement points.

![Springer]
Creatine uptake rate

The summed intensities of the $^{13}$C signal of Cr and PCr determined at day 0 till day 5 were fitted to a linear function (Fig. 2c) to yield a subject and muscle specific Cr uptake rate. Following the spectral quality criteria, this analysis could be performed in 17 out of the 20 investigated muscles of the young healthy volunteers. In males, a significant Cr uptake rate was observed in the SM, ST, and AM muscles with less in the other two muscles (Fig. 3). In females, we could observe Cr uptake in all investigated muscles, except that the G muscle of one female was too thin to place a voxel solely in that muscle. The data of the BF and ST muscles of this female did not pass the quality criteria to obtain a Cr uptake rate mainly because of low signal-to-noise ratio in some spectra. Taking all remaining muscles...
together the mean uptake rate in females was lower than in males although not significant (17 ± 26 vs. 36 ± 22 %/day with SD; p = 0.25).

To test the feasibility of the $^{13}$C MRSI assessment of muscular creatine uptake in more fragile persons, i.e., a 82-year-old male and two FSHD patients, it was necessary to decrease the number of exams during the supplementation and thereafter. The creatine supplementation was well tolerated by all participants, and no side effects were reported.

The female FSHD patient (FSHD#1) showed fatty infiltration in the AM and SM muscles, and the male FSHD patient (FSHD#2) showed severe fatty infiltration in the SM muscle, and minor fatty infiltration in the ST and BF muscles. Following the spectral and fitting quality criteria, creatine uptake rates could be determined for FSHD#1 in the ST (48 ± 101 %/day), AM (27 ± 5 %/day), and the BF (9 ± 12 %/day), and for FSHD#2 in the BF (77 ± 184 %/day). For the 82-year-old male, we observed Cr uptake in four of the five investigated muscles of which three passed the quality criteria. The SM had an uptake rate of 8 ± 15 %/day, the BF 9 ± 28 %/day, and the G 24 ± 8 %/day.

**Creatine turnover**

The Cr turnover was determined by fitting the TCr signal intensities from day 5–105 after start of supplementation, to a mono-exponential decay function (Fig. 2c). Because all Cr curves will fit to this function, even when no Cr uptake had taken place, we added a fit quality criterion that $R^2$ has to be larger than 0.5 to ensure that the fitted values indeed follow a mono-exponential decay. Only data of three muscles of male subject #2 and two muscles in the other male fulfilled this criterion. No turnover rates fulfilling the fit quality criteria could be determined for the female volunteers. For the muscles in which the Cr turnover could be determined, the rates were comparable with an average of 2.1 ± 0.7 % per day (Fig. 4).

**$T_1$ relaxation times of $^{13}$C-4 spins**

To verify that the pulse repetition time for MRSI acquisition did not cause signal saturation, we measured the $T_1$ relaxation times of the $^{13}$C spins in the hamstring muscle.
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1 3

of one healthy young male subject by analyzing the $^{13}$C-4 signals of Cr and PCr as a function of the repetition time. The $T_1$ for Cr was $341 \pm 36$ ms and for PCr $413 \pm 49$ ms. This implies that with a 45° excitation pulse and a TR of 1000 ms for the $^{13}$C MRSI acquisition, there will be little spin saturation.

$\text{PCr/TCr ratio}$

To investigate if creatine supplementation would change the $\text{PCr/TCr}$ ratio, we determined this ratio for every time point during and after the supplementation. For none of the examined muscles in the healthy young volunteers, we observed a significant change in the $\text{PCr/TCr}$ ratio during this period. An example is shown in Fig. 5 for this ratio in the ST muscle, which is around 0.75.

To investigate if the $\text{PCr/TCr}$ ratio is the same as determined in other studies, we assessed this ratio for each investigated muscle in the young volunteers averaged over all time points (Fig. 6a; Table 3). Testing each muscle against the other revealed that the $\text{PCr/TCr}$ ratio of the AM is significantly lower than that of the other muscles ($p < 0.05$), but a one-way ANOVA did not show a muscle specific effect for the $\text{PCr/TCr}$ ratio ($p = 0.32$). For all subjects and all muscles, together the average $\text{PCr/TCr}$ ratio was $0.71 \pm 0.07$ (including a small correction for differences in $T_1$ between Cr and Cr).

The average $\text{PCr/TCr}$ ratios of all investigated muscles in the old healthy male and FSHD patients were similar to the values of the young healthy subjects (see Fig. 6b), with $T_1$-corrected values of $0.71 \pm 0.03$ and $0.71 \pm 0.07$, respectively.

Discussion

In this feasibility study, we demonstrate that 3D $^{13}$C MRS imaging with oral ingestion of $^{13}$C4-creatine can be used to monitor Cr uptake and turnover rates as well as $\text{PCr/TCr}$ ratios in individual muscles of the human leg. Previously, we showed with unlocalized $^{13}$C MRS, and an RF coil next to the gastrocnemius of a male subject that the non-invasive monitoring of Cr and PCr during and after supplementation of $^{13}$C4-labeled Cr is feasible (Kan et al. 2006). Given the substantial variation in creatine uptake in different muscles, it is relevant to demonstrate that with $^{13}$C MRS in spectroscopic imaging mode, we can spatially resolve information of $^{13}$C labeled metabolites in multiple individual muscles in one exam. We applied this technique in a diverse group of subjects, including four young and one old healthy volunteer, and two patients with FSHD. In this way, the supplied Cr, and its immediate cellular product PCr, is assessed instead of the total Cr or PCr pool, as has been done with $^1$H or $^{31}$P MRS after oral Cr ingestion, e.g., (Kreis et al. 1999; Brault et al. 2007).

It is a common finding in human muscular studies of creatine uptake, assessed with biopsies, that TCr increases more than PCr during the supplementation period, e.g., (Hultman et al. 1996; McKenna et al. 1999). A study combining $^1$H and $^{31}$P measurements to determine TCr and PCr...
in the vastus lateralis (where most biopsies are taken from) did not find this (Brault et al. 2007). The authors attribute this discrepancy to higher PCr hydrolysis during the biopsy procedure because of the change in physiological condition of muscles loaded with Cr. Our single subject study using $^{13}$C MRS also did not find a change in the PCr/TCr ratio of the gastrocnemius during Cr uptake (Kan et al. 2006). In the present study, we assessed this for a few other muscles in the thigh and found no preferential increase in TCr over the supplementation period within the error of the measurements. These findings indicate a general preservation of the overall thermodynamic equilibrium of the creatine kinase reaction in muscle cells at rest, also during Cr loading.

The range of average PCr/TCr ratios of the investigated muscles (from 0.65 to 0.75) is within the range reported in the literature for this ratio from 0.6 to 0.8 (Casey et al. 1996; Mesa et al. 2002) and comparable with our previous unlocalized study of the gastrocnemius (Kan et al. 2006). The PCr/TCr ratio is similar for all the investigated muscles in the young volunteers with a somewhat lower value for the adductor magnus, which may be due to a different fiber type distribution (Johnson et al. 1973; Mesa et al. 2002).

Interestingly, the average PCr/TCr ratios in the older subject and FSHD patients were not different from the young volunteers indicating that energy balance and CK activity in the muscle of these subjects result in a similar thermodynamic equilibrium of the reaction at rest. In principle, muscle specific PCr/TCr ratios can also be determined non-invasively with $^1$H and $^{31}$P MRS recordings of the same muscle, but this has not yet been reported as such.

The average muscular Cr turnover rate of $2.1 \pm 0.7 \%$ per day is in agreement with the results of our previous $^{13}$C MRS study of a single subject and with the reported non-enzymatic breakdown rates of creatine to creatinine (Kan et al. 2006; Walker 1979; Wyss and Kaddurah-Daouk 2000). In particular, for muscles with relatively high SNR spectra (SM and AM muscles of young volunteers), the data points indicate an apparent linear uptake of labeled Cr during the 4 days supplementation. This is in agreement with previous supplementation studies and has been associated with near-saturation of the Cr transporters (Brault et al. 2007), which would suggest that uptake rates reflect creatine transporter capacity of muscles.

Cr uptake rates were variable among the five thigh muscles and subjects and varied between 0 and about 80 % per day over all subjects and muscles. It is not possible that the lack of Cr uptake in some muscles is caused by subjects not taking $^{13}$C-labeled Cr as the blood plasma samples analyzed before and during the Cr supplementation period showed similar increase in Cr and $^{13}$C–4–Cr concentration for all subjects during the supplementation period proving that they did ingest the provided $^{13}$C–Cr.

Differences in Cr response have been observed in rat hind limb muscles, with significant uptake in the gastrocnemius muscle but no response in the soleus muscle, an effect attributed to a higher contribution of type II fibers in the gastrocnemius (McMillen et al. 2001). In humans, the increases in (relative) Cr or PCr level after supplementation appear to differ among leg muscles with reported values from about 4 % for the gastrocnemius (Vandenbergh et al. 1997) to about 20 % for quadriceps muscles (Kreis et al. 1999; Smith et al. 1999). The origin of these differences is unknown; in studies addressing this issue, the proposed $^{13}$C MRSI method to assess uptake rates could be helpful.

Based on the reported values for Cr turnover rates, we estimate that to keep up with spontaneous constant Cr breakdown, a $^{13}$C signal increase in muscle spectra of 10–30 %/day is expected during the supplementation. This implies that higher uptake rates are reflecting an increase of Cr levels in the muscles. It also suggests that for muscles with an uptake rate below about 10 %/day in this study, the SNR and/or the reproducibility of the measurement and/or fitting procedure of the Cr signal was inadequate.

For this $^{13}$C MRSI study, we increased the field strength from 1.5T to 3T and the $^{13}$C enrichment from 10 to 15 %, compared with our previous $^{13}$C MRS study (Kan et al. 2006). The higher sensitivity allowed us to study $^{13}$C uptake and metabolism in individual muscles of young male subjects with sufficient SNR. However, this was less so in the females and older person and in FSHD patients, in which the quality filter only allowed to assess an uptake rate in four out of ten muscles. In the latter cases, this could be due to less Cr uptake or a lower muscular fraction. In a $^{31}$P MRS study on FSHD patients, a preferential decrease of the SNR and the PCr/ATP ratio was observed in fat infiltrated muscles (Kan et al. 2010). These results imply that for future clinical research studies with $^{13}$C MRSI, the SNR has to be increased, which can be achieved in several ways. First, the relative short $T_1$ values of the $^{13}$C spin systems in Cr and PCr ($\approx$400 ms) at 3T allow for a shorter Tr than the currently used 1000 ms, so that more scans can be acquired in the same amount of time. Second, the voxel size can be enlarged in the length direction of the muscles. Third, improved MR instrumentation can be used, such as array RF coils or higher field strength, which requires substantial investments. Fourth, the $^{13}$C enrichment of the creatine can be increased, which, however, will increase the cost of the experiment. In addition, calibrations and registrations for better reproducibility, and signal fitting with more restrictive prior knowledge, such as line width limitations, may help.

For a full non-invasive investigation of muscular creatine uptake, it would be important to also know the total amount of creatine during and after the supplementation (Nabuurs et al. 2013). As we already employ a proton RF
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coil in the current setup, this can be most easily achieved by simultaneous or alternate 1H MRS measurements (Kreis et al. 1999).

In summary, we introduce an in vivo 13C MRS imaging method to study intake and conversion of 13C labeled metabolites in skeletal muscles. We demonstrate that this allows for direct monitoring of supplied 13C4-labeled Cr for subject and muscle specific determination of PCr/TCr ratios, and Cr turnover and uptake rates.

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Compliance with ethical standards

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Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Written informed consent was obtained from all participants.

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