Calpain 6 inhibits autophagy in inflammatory environments: A preliminary study on myoblasts and a chronic kidney disease rat model

YUE YUE ZHANG, LI JIE GU, NAN ZHU, LING WANG, MIN CHAO CAI, JIE SHUANG JIA, SHU RONG and WEI JIE YUAN

Division of Nephrology, Shanghai General Hospital, Shanghai Jiaotong University School of Medicine, Shanghai 200080, P.R. China

Received March 16, 2021; Accepted June 30, 2021

DOI: 10.3892/ijmm.2021.5027

Abstract. A non-classical calpain, calpain 6 (CAPN6), can inhibit skeletal muscle differentiation and regeneration. In the present study, the role of CAPN6 in the regulation of the autophagy of myoblasts in vitro was investigated. The underlying molecular events and the CAPN6 level in atrophic skeletal muscle in a rat model of chronic kidney disease (CKD) were also investigated. In vitro, CAPN6 was overexpressed, or knocked down, in rat L6 myoblasts to assess autophagy and related gene expression and co-localization. Subsequently, myoblasts were treated with a mixture of cytokines, and relative gene expression and autophagy were assessed. A rat model of CKD for muscle atrophy was established, and blood chemical level and the expression of CAPN6 in muscle were assessed. The data revealed that the knockdown of CAPN6 in rat myoblasts resulted in increased microtubule-associated protein 1 light chain 3 (LC3) levels, while its overexpression decreased LC3 levels and impaired autophagy. Additionally, it was observed that the co-localization of mammalian target of rapamycin (mTOR) and lysosomal-associated membrane protein 1 (LAMP1), a lysosomal marker, proteins was increased. In addition, mTOR, Raptor and α-tubulin (a marker of microtubules) increased in the CAPN6 overexpression group. However, inflammatory cytokines, such as interleukin (IL)-6, tumor necrosis factor (TNF)-α, interferon (INF)‑γ and lipopolysaccharides upregulated CAPN6 expression, inhibited L6 myoblast autophagy and stabilized mTOR activity. Furthermore, the animal model successfully mimicked human disease as regards an increase in body weight, and a reduction in muscle mass, cross-sectional area and blood biomarker concentrations; a slight increase in CAPN6 mRNA and protein levels in muscles was observed. Finally, the data of the present study suggested that CAPN6 reduced autophagy via the maintenance of mTOR signaling, which may play a role in CKD-related muscle atrophy. However, future studies are required to determine whether CAPN6 may be used as an intervention target for CKD-related skeletal muscle atrophy.

Introduction

Chronic kidney disease (CKD) is associated with early-age mortality, a decrease in the quality of life of affected individuals and increased health care costs (1). CKD alters complex metabolic processes that affect muscular homeostasis, resulting in a loss in muscle mass and, ultimately, in muscle atrophy (2,3). Approximately 16 to 54% of patients with CKD are malnourished (4). The term protein-energy wasting (PEW) has been suggested to describe this syndromic uremic malnutrition (5) and to denote the concurrent losses in protein and energy storage (6), while skeletal muscle atrophy is the main PEW characteristic. As CKD progresses, the risk of PEW increases (7), ultimately increasing the risk of mortality (8). Therefore, the identification of the PEW-inducing mechanisms and the exploration of possible interventions may aid in the provision of practical and effective treatment approaches for the clinical prognosis of patients with CKD.

Autophagy and mitophagy can play an important role in CKD-related muscle atrophy (9). Autophagy is a part of the lysosomal degradation pathway and its main function is to remove unnecessary or dysfunctional components from cells, playing an important role in the maintenance of cell homeostasis (10-12). Demarchi et al (13) found that autophagy was damaged in cells with a defective calpain small subunit. In addition, calpain-6 (CAPN6) can antagonize the effects of other classical forms of calpain (14), indicating that CAPN6 can inhibit autophagy.

CAPN6 is a non-classical calpain (cannot degrade proteins) and is mainly expressed in fetal muscle and the placenta. CAPN6 expression is reduced after birth, but is upregulated...
in various tumor tissues (15). A previous study revealed that CAPN6 deficiency promoted skeletal muscle development and regeneration, whereas it suppressed differentiation (16). Another study, involving DNA microarray cluster analysis, revealed that CAPN6 expression was upregulated in the sera of patients with type 2 diabetic nephropathy (17). The Gene Expression Omnibus (GEO) database on CAPN6 expression in patients with CKD revealed that CAPN6 expression was higher in CKD renal tissues than in control tissues (https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE48944) (18). However, Andrique et al (19) reported that CAPN6 promoted autophagy and prevented senescence in hypoxic environments to regulate sarcoma stem-cell fate and tumor progression. Therefore, it is important to understand the role of CAPN6 and its regulatory effects on autophagy in CKD.

Autophagy can be regulated by the canonical mammalian target of rapamycin (mTOR)/Unc-51 like autophagy activating kinase 1 (ULK1/2) and 5'AMP-activated protein kinase (AMPK) pathways (20). mTOR can form the mTOR complex 1 (mTORC1)- mTOR, Raptor, mammalian lethal with SEC13 protein 8 (mLST8) and proline-rich Akt substrate 40 (PRAS40) (21-23), and plays an important role in negative regulation of these results, the present study aimed to elucidate the underlying mechanisms through cytokines may increase CAPN6 expression in muscles. Therefore, the role of CAPN6 in the regulation of autophagy in myoblasts in vitro and the underlying molecular events were investigated in the present study. In addition, the CAPN6 levels in atrophic skeletal muscle in a rat model of CKD were evaluated, in order to primarily explore the role of CAPN6 in CKD-related muscle atrophy.

Materials and methods

Animals and animal experiments. All animal experiments were approved by the Animal Care and Use Committee of Shanghai Jiao Tong University (Shanghai, China) and followed the Guidelines of the Care and Use of Laboratory Animals issued by the Chinese Council on Animal Care (project no. 2015DW001). Specifically, male Sprague-Dawley rats (200-250 g body weight) were purchased from the Chinese Academy of Sciences, bred, and maintained at the Animal Center Laboratory of Shanghai General Hospital. All animals were housed in a specific pathogen-free facility. They were fed a standard diet and had free access to water. The rats were randomly assigned to either a 5/6 nephrectomy group or a sham operation group, and received surgical procedures according to a previous study (31). Briefly, the rats were anesthetized by intraperitoneal injection of sodium pentobarbital (40 mg/kg) and received the 5/6 nephrectomy by surgical resection of the upper and lower thirds of the left kidney followed by right nephrectomy 7 days later. In the control group, only a sham operation was performed. During the experimental period, the animals were monitored two to three times per week for potential signs of suffering, mainly a weight loss >20% and significant changes in their behavior, mobility or body posture. In the case that the rats met one of these criteria, euthanasia would have been warranted on the same day in order to prevent further suffering. Animals were kept for 6 months. One CKD rat died in the late experimental period, and all control rats survived, similar to previous studies (22,23). Following adequate anesthesia with sodium pentobarbital (40 mg/kg) intraperitoneal injection, the bodyweight of each rat was recorded and blood samples were then collected through cardiac puncture, in order to measure creatinine, blood urea nitrogen (BUN), albumin (Alb), total cholesterol (TC) and triglyceride (TG) serum levels. Gastrocnemius muscle samples were collected and used to measure muscle wet weight, perform reverse transcription-quantitative PCR (RT-qPCR) and western blot analyses. Finally, the rats were sacrificed by decapitation immediately after the experimental procedure when the rats were still under deep anesthesia. Death was further confirmed by checking for the onset of rigor mortis (34).

Hematoxylin and eosin (H&E) staining. Gastrocnemius muscle samples were fixed in 4% freshly made paraformaldehyde and processed for embedding in paraffin and sectioning. Tissue sections were treated with 10% SDS solution and then dehydrated in a series of ethanol solutions before being infiltrated with paraffin. Tissue sections at a thickness of 4 µm were stained with H&E, and used to measure muscle wet weight, perform reverse transcription-quantitative PCR (RT-qPCR) and western blot analyses. Cross-sectional areas (CSAs) were analyzed using Image-Pro Plus 6.0 software (Media Cybernetics, Inc.) after counting at least 100 muscle fibers per muscle.

Cells and cell culture. Rat L6 myoblasts were purchased from The Cell Bank of Type Culture Collection of the Chinese Academy of Sciences (GCR 4), and were passaged according to previous studies (35,36). L6 cells were seeded in 6-well plates (1x10^5 cells per well) in Dulbecco’s modified Eagle’s medium (DMEM; Gibco; Thermo Fisher Scientific, Inc.), supplemented with 10% fetal bovine serum ([FBS]; Gibco; Thermo Fisher Scientific, Inc.) and 1% penicillin/streptomycin. Afterwards, the L6 myoblasts were incubated in a humidified incubator with 5% CO₂ at 37°C overnight. Then cell culture medium was replaced with DMEM containing only 2% horse serum to initiate differentiation for 48 h.

To mimic the conditions of CKD in rats and patients in vivo, L6 myoblasts were exposed to four different inflammatory agents [2 ng/ml IL-6; (400-06, Peprotech), 2 ng/ml TNF-α, 200 ng/ml IFN-γ, and 200 ng/ml TNF-α] for 1-3 min, using standard procedures and observed under a light microscope (DFC550; Leica Microsystems, Inc.). Cross-sectional areas (CSAs) were analyzed using Image-Pro Plus 6.0 software (Media Cybernetics, Inc.) after counting at least 100 muscle fibers per muscle.
expression levels were calculated using the 2-ΔΔCT method and repeated three times. The cAPN6 relative mRNA levels were evaluated.

Cell transfection. Plasmids carrying CAPN6 shRNA (hU6-MCS-SV40-Neomycin-CAPN6 RNAi and CAPN6-α) and shRNA negative control were purchased from GeneChem, Inc. and the CAPN6 CRISPR activation plasmid (cat. no. sc-437325-ACT) and the control CRISPR activation plasmid (cat. no. sc-437275) were obtained from Santa Cruz Biotechnology, Inc. Plasmids carrying Raptor shRNA (phb-u6-mcs-pgk-puro-Raptor RNAi and Raptor−) and shRNA negative control were purchased from Hanbio Biotechnology Co., Ltd. For cell transfection, L6 cells were grown overnight and transiently transfected at room temperature using OptiMEM medium with Lipofectamine 2000® (Invitrogen; Thermo Fisher Scientific, Inc.) and reverse transcribed into cdNA using the High Capacity cdNA Reverse Transcription kit (cat. no. sc-20011; Santa Cruz Biotechnology, Inc.). Primers used were as follows: CAPN6 forward, 5'-TGT TGGGCTGTTCAGGAGTC-3' and reverse, 5'-TGGGAAAGCA AGTGTGCAATC-3'; and glyceraldehyde 3-phosphate dehydrogenase (GAPDH) forward, 5'-GTCGGTGTGAACGGATTTTG-3' and reverse, 5'-TCCATTCTCAGCCTTGAC-3'.

Autophagy assay. Red and green fluorescent protein-tagged microtubule-associated protein 1 light chain 3 (RFP-GFP-LC3) adenoviral vectors (Hanbio Biotechnology Co., Ltd.) was used to transfect the L6 cells for the measurement of autophagy levels, using OptiMEM medium with Lipofectamine 2000® (Invitrogen; Thermo Fisher Scientific, Inc.), according to the manufacturer's protocol. The final concentration of the plasmids was 10 μl/ml. The transfection efficiency was inspected with a Leica Microsystems GmbH confocal microscope (Leica DM6000B). The RFP-GFP-LC3 levels in transfected cells was also visualized using a Leica Microsystems GmbH confocal microscope (Leica TCS SP8) and quantified using Image-Pro plus 6.0 (Media Cybernetics, Inc.).

RT-qPCR. Total cellular RNA was isolated from the tissues and cells using TRIzol® reagent (cat. no. 15596-026; Invitrogen; Thermo Fisher Scientific, Inc.) and reverse transcribed into cdNA using the High Capacity cdNA Reverse Transcription kit (cat. no. K1622; Thermo Fisher Scientific, Inc.) according to the manufacturer's protocols. qPCR was performed using SYBR-Green (cat. no. F-415XL; Thermo Fisher, Inc.) in an ABI PRISM Sequence Detector System 7300 (Applied Biosystems; Thermo Fisher Scientific, Inc.). Conditions were set to initial 95°C for 10 min, then 40 cycles of 95°C for 15 sec and 60°C for 60 sec. Each experiment was performed in triplicate and repeated three times. The CAPN6 relative mRNA expression levels were calculated using the 2-ΔΔCT method (37). The primers used were as follows: CAPN6 forward, 5'-TGCCTTCAACAGAG 3' and reverse, 5'-TGGGAAGCA AGTGTGCAATC-3'; and glyceraldehyde 3-phosphate dehydrogenase (GAPDH) forward, 5'-GTCGGTGTGAACGGATTTTG-3' and reverse, 5'-TCCATTCTCAGCCTTGAC-3'.

Western blot analysis. Tissue and cell samples were pulverized and lysed in the radioimmunoprecipitation assay (RIPA) buffer (Beyotime Institute of Biotechnology) at 4°C for 2 h. The lysates were centrifuged at 10,000 x g at 4°C for 10 min to collect the supernatant into separate tubes. The quality and concentration of protein were detected using a NanoDrop spectrophotometer (Thermo Fisher Scientific, Inc.). Protein samples (20 μg) were separated with sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and electro-transferred onto nitrocellulose membranes (EM Millipore). The membranes were incubated in 5% skim milk in phosphate-buffered saline (PBS)-Tween 20 (PBS-T) at room temperature for 1 h, and subsequently with primary antibodies at 4°C overnight. The following primary antibodies used were purchased from Cell Signaling Technology, Inc.: anti-LC3 (1:1,000, cat. no. 2775), GAPDH (1:2,000, cat. no. 5174), phosphorylated (p-)eukaryotic translation initiation factor 4E binding protein 1 (4EBP-1; 1:1,000, cat. no. 2855), 4EBP-1 (1:1,000, cat. no. 9452); p-p70s6k1 (1:1,000, cat. no. 9234), p70s6k1 (1:1,000, cat. no. 9202) and (mTOR; 1:1,000, cat. no. 2983). Anti-CAPN6 (1:1,000, cat. no. ab76974) and Raptor (1:1,000, cat. no. ab40768) antibodies from Abcam were also used. GAPDH antibody was used as a loading control for the muscle tissues. Afterwards, the membranes were washed three times with PBS-T, then incubated with horseradish peroxidase-conjugated secondary anti-rabbit IgG (1:1,000, cat. no. A0208; Beyotime Institute of Biotechnology), or anti-mouse IgG (1:1,000, cat. no. A0216; Beyotime Institute of Biotechnology), for 1 h at room temperature. Positive protein bands were visualized using an enhanced chemiluminescence (ECL) substrate kit (cat. no. WBKLS0100; EMD Millipore), exposed to X-ray films and quantified using Tanon-5200 software (Tanon Science & Technology Co., Ltd.).

Immunofluorescence staining. First, cell slides were washed with PBS (0.02 M) to remove the culture medium, and fixed with 4% formaldehyde for 30 min. Subsequently, the slides were washed three times for 3 min each with PBS (0.02 M) prior to permeabilization with Triton X-100 (0.5%) for 10 min. Consequently, the slides were washed three times with PBS (0.02 M), for 3 min each. Cells were blocked with 1% BSA for 1 h and washed with PBS (0.02 M) for 3 min, 3 times. Diluted primary antibodies were added drop by drop to each cell slide, and the slides were then placed in a wet box and incubated at 4°C overnight. Primary antibodies used in this experiment included Raptor (1:200, cat. no. ab5454; Abcam), mTOR (1:200, cat. no. 2983; Cell Signaling Technology, Inc.), lysosomal-associated membrane protein 1 (LAMP1; 1:500, cat. no. sc-20011; Santa Cruz Biotechnology, Inc.), α-tubulin (1:1,000, cat. no. 3873; Cell Signaling Technology, Inc.). A secondary antibody was then added in a dropwise manner, and the slides were placed into a wet box and incubated at 20°C for 1 h. The secondary antibodies used, included goat anti-rabbit IgG (FITC;1:1,000, ab67177) and goat anti-mouse IgG (TR;1:1000, ab5766), purchased from Abcam. DAPI (1:500, Beyotime Institute of Biotechnology) was used for nuclei staining at room temperature for 1 min. The slides were stored at -20°C until further analysis. Images were recorded using a fluorescence microscope (Olympus Corporation). A total of five randomly selected fields of each slide were selected and analyzed using Image-Pro plus 6.0 software (Media Cybernetics, Inc.).

Statistical analysis. Data are presented as the mean ± standard deviation (SD) and were statistically analyzed using SPSS 17.0.
ZHANG et al.: CALPAIN 6 IN AUTOPHAGY IN CKD

In particular, data with a normal distribution were analyzed using one-way analysis of variance (ANOVA), followed by pairwise comparisons with the Tukey's test. Data with unequal and non-parametric features were analyzed using ANOVA on ranks followed by the Dunn's method for pairwise comparisons. Comparisons between two groups were analyzed with an independent Student's t-test. P≤0.05 was considered to indicate a statistically significant difference.

Results

CAPN6 rat L6 myoblast autophagy reduction and the possible underlying mechanisms. To explore the involvement of CAPN6 in the regulation of myoblast autophagy, the expression of the autophagy-related genes, LC3 and p62, in rat L6 myoblast cells were examined. First, CAPN6 overexpression and knockdown was induced in L6 cells (Fig. S1). CAPN6 shRNA decreased CAPN6 protein levels by 55.75% and increased the ratio of LC3II/I by 124.815%, whereas CAPN6 cDNA increased the CAPN6 levels by 23.6% and decreased the ratio of LC3II/I by 45.03% (Fig. 1). This was also confirmed by p62, a cargo protein degraded inside autolysosomes, protein level detection. The level of p62 decreased when CAPN6 expression decreased (Fig. 1).

To examine the autophagic flux status, L6 myoblasts were transfected with RFP-GFP-LC3 plasmid, according to a previous study (38). The green fluorescent protein (GFP) level is quenched in the lysosomal environment and the red fluorescent protein (RFP) signal is more stable in the acidic environment according to a previous study (39). Thus, the autophagosomes and autolysosomes were labeled with a yellow (green and red) or red color, respectively. Through the detection and the analysis of the two different fluorescent signals, the autophagic flux was monitored. After culturing the myoblasts for 48 h with CAPN6 cDNA, decreased red fluorescence was observed in the CAPN6 group, in comparison with the CRISPR-transfected groups (Control-CRISPR group). This indicated that CAPN6 may decrease autophagy (Fig. 1).

Furthermore, the mechanism responsible for the effects of CAPN6 on autophagy was explored. It was observed that the co-localization of mTOR and LAMP1 proteins (a lysosomal marker) was increased in the CAPN6 overexpression group (CAPN6 group), indicating an increased combination of mTOR and lysosomal degradation. Additionally, the co-localization of mTOR, Raptor and α-tubulin (a marker of microtubules) in the CAPN6 group indicated an increased combination of mTORC1 and microtubules. These results indicated that a high CAPN6 expression was positively related...
to mTORC1 combined with lysosomal and microtubules, and this may be a mechanism through which CAPN6 inhibits autophagy (Fig. 2).

Following a decrease in mTORC1 through transfection with Raptor shRNA, it was revealed that the co-localization of mTOR and LAMP1 proteins, mTOR and α-tubulin, Raptor and α-tubulin decreased in the CAPN6 overexpression + Raptor shRNA-transfected group (CAPN6 + Raptor shRNA group). In addition, an increase in red fluorescence was observed in the CAPN6 + Raptor shRNA group, as compared with the CAPN6 group. This indicated that mTORC1 combined with lysosomal or microtubules plays an important role in CAPN6 inhibiting autophagy flux (Fig. 2).

**Upregulation of CAPN6 by inflammatory cytokines.** L6 myoblasts were exposed to 2 ng/ml IL-6, 2 ng/ml TNF-α, 2 ng/ml INF-γ and 10 ng/ml LPS separately and it was demonstrated that the protein expression of CAPN6 increased, particularly in the IFN-γ-treated L6 myoblasts (Fig. 3). The mRNA levels also increased when the cells were exposed to the four inflammatory agents simultaneously and in a time-dependent manner. The expression levels increased following 6 h of treatment and were higher at 24 h (Fig. 3).

**CAPN6/mTORC1 activity plays a role in the inhibition of autophagy by inflammatory cytokines.** Subsequently, the effects of CAPN6 on autophagy in myoblasts exposed to the four inflammatory agents were assessed. CAPN6 expression significantly increased in the cytokine mixture-treated L6 myoblasts (M group), while the level of LC3II/I decreased significantly. LC3II/I expression increased following CAPN6 knockdown using shRNA in the cytokine mixture-treated L6 myoblasts (M + shRNA group; Fig. 4). The autophagic was also examined with fluorescence. It was observed that the fluorescence was not significantly altered in the M group; however, fluorescence increased in the M + shRNA group, suggesting an increase in the autophagic flux (Fig. 4C).

Finally, the expression and activity of mTORC1 in L6 myoblasts following treatment with the control or cytokine mixture (M group) was evaluated and an increase in mTOR, p-p70s6k1/p70S6K1 and p-4EBP1/4EBP1 expression was observed. Additionally, CAPN6 knockdown (M + shRNA...
ZHANG et al.: Calpain 6 in Autophagy in CKD

However, Raptor expression was not significantly altered in the three groups.

CAPN6 expression is relatively high in CKD. In the in vitro experiments, a rat model of CKD was established. The rats exhibited a decrease in body weight, and reduced muscle mass (Fig. 5). CAPN6 expression is relatively high in CKD. In the in vitro experiments, a rat model of CKD was established. The rats exhibited a decrease in body weight, and reduced muscle mass

Figure 3. Effects of cytokines on gene expression in L6 myoblasts. (A) L6 myoblasts were grown and treated with 2 ng/ml IL-6, 2 ng/ml TNF-α, 2 ng/ml INF-γ and 10 ng/ml LPS individually for 24 h, then subjected to western blot analysis. (B) L6 myoblasts were grown and treated with the cytokine mixture for 24 h, then subjected to RT-qPCR. The experiment was repeated three times. The cytokine mixture was prepared as follows: 2 ng/ml IL-6, 2 ng/ml TNF-α, 2 ng/ml INF-γ and 10 ng/ml LPS. (C) L6 myoblasts were grown and treated with cytokine mixture for 6 and 24 h, then subjected to RT-qPCR analysis. (D) L6 myoblasts were grown and treated with the cytokine mixture for 6 and 12 h, then subjected to western blot analysis. *P<0.05 as compared with the control group. #P<0.05 in comparison with the 6-h group. IL, interleukin; TNF, tumor necrosis factor; INF, interferon; LPS, lipopolysaccharide.

Figure 4. Effects of CAPN6 knockdown on CAPN6 and LC3 expression regulation in rat L6 myoblasts under different conditions. (A) L6 myoblasts were grown, then treated with M (cytokine mixture), M + shRNA (cytokine mixture + transfected CAPN6 shRNA) to assess CAPN6 mRNA expression, evaluated by RT-qPCR. (B) CAPN6 and LC3 protein expression assessed by western blot analysis. (C) LC3 protein expression assessed by immunofluorescence (magnification, x400). The cytokine mixture was prepared as follows: 2 ng/ml IL-6, 2 ng/ml TNF-α, 2 ng/ml INF-γ and 10 ng/ml LPS. *P<0.05 in comparison with the control group, #P<0.05 in comparison with the M group. CAPN6, calpain 6; LC, autophagy-related protein light-chain; M, cytokine mixture; M + shRNA, cytokine mixture plus sh-CAPN6.
Figure 5. Comparison of indicated biomarker levels under different conditions. Protein expression of mTOR, Raptor, p-p70S6K1/p70S6K1 and p-4EBP1/4EBP1 for the control, M (cytokine mixture) and M + shRNA (cytokine mixture + CAPN6 shRNA-transfected). The cytokine mixture was prepared as follows: 2 ng/ml IL-6, 2 ng/ml TNF-α, 2 ng/ml INF-γ and 10 ng/ml LPS. *P<0.05 in comparison with the control group, ¦P<0.05 in comparison with the M group. CAPN6, calpain 6; M, cytokine mixture; M + shRNA, cytokine mixture + shCAPN6.

Figure 6. Establishment of the rat model of CKD. Male Sprague-Dawley rats with body weights ranging from 200 to 250 g were randomly assigned to the CKD or control groups (n=8, per group). (A) Muscle and body weights of the rats. (B) H&E staining (magnification, x40). Arrows indicate skeletal muscle fiber. (C) The graph summarizes the CSA of the gastrocnemius muscle in Control and CKD rats. *P<0.05 in comparison with the control group. CKD, chronic kidney disease; H&E, hematoxylin and eosin; CSA, cross-sectional area.
Table I. Comparison of serum urea nitrogen, creatinine, albumin, triglyceride and cholesterol levels between the control and CKD group rats.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>CKD</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUN (mmol/l)</td>
<td>5.65±0.94</td>
<td>18.38±5.49</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cr (µmol/l)</td>
<td>31.29±3.97</td>
<td>73.99±23.50</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Alb (g/l)</td>
<td>24.22±2.03</td>
<td>20.67±4.04</td>
<td>0.027</td>
</tr>
<tr>
<td>TC (mmol/l)</td>
<td>1.19±0.07</td>
<td>2.02±0.28</td>
<td>0.015</td>
</tr>
<tr>
<td>TG (mmol/l)</td>
<td>2.65±0.20</td>
<td>0.31±0.19</td>
<td>0.010</td>
</tr>
</tbody>
</table>

CKD, chronic kidney disease; BUN, blood urea nitrogen; Cr, creatinine; Alb, albumin; TC, total cholesterol; TG, triglyceride.

and muscle CSA (Fig. 6). Blood chemical levels were similar to those similar to those of CKD patients (9), including an increase in BUN, serum creatinine and TC levels, and lower TG and Alb levels (Table I). CAPN6 mRNA and protein expression levels in the gastrocnemius muscles of rats with CKD were also examined, and it was revealed that there was a non-significant increase only (Fig. 7).

Discussion

In the present study, a novel mechanism, to the best of our knowledge, was revealed, concerning the inhibition of CKD-induced autophagy activation: i) CAPN6 acted with mTOR complex 1 to impair autophagy activity in myoblasts; ii) CAPN6 expression did not increase significantly in the CKD rat muscle atrophy model. Future studies are required, however, to investigate CAPN6 targeting as a novel strategy for the attenuation of CKD-induced skeletal muscle atrophy.

It has been reported that autophagy can help muscle mass maintenance, since the autophagic flux is important for preserving muscle mass and myofiber integrity, and autophagy inhibition is associated with myofiber degeneration and weakness in muscle disorders (40). Additionally, excessive autophagy has been reported to aggravate cell damage through the engulfment of proteins, mitochondria and other organelles, affecting cell health and homeostasis (12). Previous studies have demonstrated that hyperactive autophagy and mitophagy may play important roles in CKD-related muscle atrophy (9,41).

In the present study, it was demonstrated that CAPN6 expression impairs autophagy activity in rat L6 myoblasts, whereas CAPN6 knockdown in myoblasts induced autophagy, evidenced by an increase in LC3 expression. As mTORC1 is recruited to the lysosome and is subsequently activated (42), the possible mechanism of CAPN6-induced autophagy inhibition was further explored in the present study. It was demonstrated that mTORC1, combined with lysosomal or microtubules, may play an important role in CAPN6 autophagy flux inhibition.

It has been previously demonstrated that CKD rats exhibit an increase in circulating IL-6 and TNF-α (30,41,43-45). CAPN6 activation and muscle protein wasting can occur in conditions associated with inflammation, as for example in relation to diabetes, acidosis, excess angiotensin II, cancer cachexia and aging. In the present study, it was revealed that CAPN6 knockdown in cytokine-treated myoblasts resulted in an increase in the LC3 expression level. However, LC3 expression was not significantly altered when CAPN6 expression increased. Indirectly, this may also indicate the role of CAPN6 in autophagy, and it was speculated that an increase in cytokine levels may stimulate CAPN6 expression, in order to alleviate its act on muscle wasting. No evidence was found in support of a significant induction in CAPN6 in atrophic gastrocnemius muscles in a rat model of CKD; thus, it was speculated that there may be other factors inhibiting CAPN6 expression in CKD, including fasting, insulin/insulin growth factor-1 (IGF-1) signal (46), glucocorticoids (47) and inflammation (48), that may also influence autophagy in vivo.

In a previous study, it was reported that CAPN6 deficiency promoted embryonic skeletal muscle development (16). However, CAPN6 expression was induced in adult mouse skeletal muscle regeneration following cardiotoxin treatment, indicating that CAPN6 was able to inhibit adult mouse skeletal muscle differentiation (16). In fact, muscle regeneration, in response to various stimuli or injuries, will activate quiescent muscle stem cells and cause their differentiation into the myotube and myofiber cells, accordingly (49). Another study revealed that CAPN6 mRNA was exclusively expressed in developing skeletal and heart muscles, although it was also observed in specific types of cells in the lungs, kidneys, and placenta and various epithelial cell types (50). This was indicative of the role of CAPN6 in muscle development and regeneration. Taken together, it can be hypothesized that CAPN6 may inhibit skeletal muscle differentiation and regeneration through autophagy suppression.
In conclusion, the present study demonstrated that CAPN6 overexpression may downregulate autophagy. However, the balance concerning its detrimental vs. protective roles warrants further elucidation, particularly through in vivo studies. The present study was a proof-of-principle study, and did not present data concerning the evaluation of autophagy marker levels in the gastrocnemius muscles and the canonical mTOR/ULK1/2 and AMPK pathways regulating autophagy. Therefore, further studies are required in order to confirm the role of CAPN6 in the regulation of autophagy in CKD-induced skeletal muscle atrophy.

Acknowledgements

Not applicable.

Funding

The present study was supported in part by a grant from the Shanghai Youth Science and Technology Excellence Plan Project 2019 (grant no. 19YF1439100), and in part by the National Natural Science Foundation of China (grant no. 81900671).

Availability of data and materials

The analyzed datasets generated during this study are available from the corresponding author on reasonable request.

Authors' contributions

YYZ and LJG contributed to the acquisition, analysis and interpretation of all the raw data. All the authors have read and approved the final version of the manuscript for submission.

Ethics approval and consent to participate

All animal protocols were approved by the Animal Care and Use Committee of Shanghai Jiao Tong University (Shanghai, China) and followed the Guidelines of the Care and Use of Laboratory Animals issued by the Chinese Council on Animal Research (project no. 2015DW001).

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References


