Eugenol mimics exercise to promote skeletal muscle fiber remodeling and myokine IL-15 expression by activating TRPV1 channel

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Abstract

Metabolic disorders are highly prevalent in modern society. Exercise mimetics are defined as pharmacologic compounds that can produce the beneficial effects of fitness. Recently, there has been increased interest in the role of eugenol and transient receptor potential vanilloid 1 (TRPV1) in improving metabolic health. The aim of this study was to investigate whether eugenol acts as an exercise mimetic by activating TRPV1. Here, we showed that eugenol improved endurance capacity, caused the conversion of fast to slow muscle fibers, and promoted white fat browning and lipolysis in mice. Mechanistically, eugenol promoted muscle fiber type transformation by activating TRPV1-mediated CaN signaling pathway. Subsequently, we identified IL-15 as a myokine that is regulated by the CaN/Nuclear factor of activated T cells cytoplasmic 1 (NFATc1) signaling pathway. Moreover, we found that TRPV1-mediated CaN/NFATc1 signaling, activated by eugenol, controlled IL-15 levels in C2C12 myotubes. Our results suggest that eugenol may act as an exercise mimetic to improve metabolic health via activating the TRPV1-mediated CaN signaling pathway.

Keywords: eugenol, exercise mimetic, IL-15, myokines, skeletal muscle fiber remodeling, TRPV1

Introduction

Due to the lack of regular exercise among many individuals (***Carlson et al., 2010***), metabolic diseases are highly prevalent in modern society (***Hoehn et al., 2010***). To address this issue, pharmacological interventions have been considered as potential treatments. Exercise mimetics are pharmacologic compounds that produce fitness benefits (***Fan and Evans, 2017***). Although some synthetic exercise mimetics such as AICAR (AMPK activator), GW501516 (PPARδ activator), SRT1720 (SIRT1 activator), and GSK4716 (ERRγ activator) have been used to improve fitness (***Feige et al., 2008; Narkar et al., 2008; Rangwala et al., 2010***), the safety and health of each drug must be considered. In recent years, plant extracts such as resveratrol, lycium barbarum and epicatechin have demonstrated potential as a new class of low-toxin exercise mimetics (***Meng et al., 2020; Nogueira et al., 2011; Wen et al., 2020***). Therefore, it is of great significance to discover natural medicinal and edible plants that have mimetic effects of exercise.

Based on their metabolism and contractile properties, muscle fibers are commonly divided into slow oxidative fibers (muscle fibers that express myosin heavy chain (MyHC) I) and fast glycolytic/oxidative fibers (muscle fibers that express MyHC IIa, MyHC IIx, or MyHC IIb) (***Schiaffino and Reggiani, 2011***). Different muscle fibers exhibit a high degree of plasticity and are regulated by exercise (***Egan and Zierath, 2013***). The increased proportion of slow muscle fibers contributes to the enhancement of mitochondrial biogenesis and lipid metabolism (***Carlson et al., 2010***). Therefore, one of the benefits of exercise is to treat metabolic disorders by promoting slow muscle fiber remodeling (***Duan et al., 2017***). In addition, it has been increasingly recognized that myokines released by skeletal muscle play an essential role in mediating the benefits of exercise. Myokines are defined as cytokines or peptides that are released from skeletal muscle cells, which exert autocrine, paracrine, or endocrine effects (***Pedersen and Febbraio, 2012***). As a medium of crosstalk between muscles and other organs, myokines exert systemic regulation of exercise by acting on the muscle, fat, liver, pancreas, and other organs, effectively improving insulin resistance,

obesity, and metabolic disorders of type 2 diabetes (***Severinsen and Pedersen, 2020***). Therefore, another potential effect of exercise is to induce the release of myokines (***Fan and Evans, 2017***). Although many previous studies have discovered plant extracts as exercise mimetics by promoting slow oxidative muscle fiber, few studies have investigated the effect of exercise mimetics on the release of myokines.

Eugenol is a safe natural compound extracted from clove oil and various plant spices such as basil, bay leaves, and cinnamon (***Kaur et al., 2010***). Eugenol exhibits a variety of biological activities, including antioxidative (***Magalhães et al., 2019***), antibacterial (***Devi et al., 2010***), anti-inflammatory (***Magalhães et al., 2019***) and anti-cancer activities (***Lesgards et al., 2014***). Recent studies have also suggested that eugenol could be a promising therapeutic drug for preventing diabetes and obesity (***Al-Trad et al., 2019; Jung et al., 2012; Mnafgui et al., 2013; Srinivasan et al., 2014***), indicating its potential as an exercise mimetic. In addition. as a member of the transient receptor potential (TRP) channel family, TRP vanilloid 1 (TRPV1), also known as the capsaicin receptor, has been reported to improve endurance capacity and energy metabolism (***Luo et al., 2012***), counter obesity (***Baskaran et al., 2016***), and intervene diabetes (***Wang et al., 2012***), making it a potential target protein for discovering exercise mimetics.

Eugenol contains a vanilloyl fragment that may bind to TRPV1 similarly to capsaicin, implying that eugenol might exert its biological activity via TRPV1 (***Harb et al., 2019***). It has been found that eugenol activates TRPV1 in a heterologous expression system and rat trigeminal ganglion neurons (***Xu et al., 2006; Yang et al., 2003***). Furthermore, a recent study demonstrated that eugenol activated TRPV1 in skeletal muscle (***Jiang et al., 2022***). TRPV1 is an important Ca^{2+} entry pathway contributing to increase intracellular Ca^{2+} (***Nilius et al., 2007***), suggesting that TRPV1 may regulate many biological processes through Ca^{2+}-dependent signaling pathways. As a Ca^{2+}-dependent signaling, calcineurin (CaN) is a core signaling to promote fast to slow muscle fiber transformation (***Sakuma and Yamaguchi, 2010***). Additionally, CaN signaling plays an essential

role in regulating the expression of myokine IL-6 (***Banzet et al., 2005; Banzet et al., 2007***). Therefore, we hypothesize that eugenol, as an exercise mimetic, promotes the release of myokines and fast to slow muscle fiber transformation via the TRPV1-mediated CaN signaling pathway. The primary objective of this study is to investigate this hypothesis.

Results

Eugenol promotes fast to slow muscle fiber transformation in mice and in C2C12 myotubes

As depicted in Figure 1A and B, eugenol did not have any effect on the body weight or skeletal muscle weight in mice. However, the skeletal muscle in the EUG50 and EUG100 groups exhibited a redder muscle color (Figure 1C), indicating a shift from fast to slow muscle fiber in these two groups. Further experiments showed that EUG50 and EUG100 increased the expression of slow MyHC and decreased the expression of fast MyHC protein in GAS and TA muscles (Figure 1D and E). Additionally, the mRNA expression of *MyHC I*, *MyHC IIa*, *MyHC IIx*, and *MyHC IIb* was generally consistent with protein expression (Figure 1G). As our *in vivo* studies demonstrated that the EUG200 group had no effect on muscle fiber type, we suspected that high doses of eugenol may have no impact on muscle fiber type. Therefore, we selected a broad range of eugenol doses (0-200 μM) based on the safe range of eugenol doses determined by the CCK-8 assay (Figure 1-figure supplement 1) to treat C2C12 myotubes and replicate these results *in vivo*. As indicated in Figure 1F, 12.5-50 μM eugenol boosted slow MyHC expression, while 12.5-100 μM eugenol decreased fast MyHC expression. Furthermore, as shown in Figure 1H, 100 μM eugenol increased the mRNA expression of *MyHC I*, and 12.5-100 μM eugenol increased the mRNA expression of *MyHC IIa*, whereas 50 μM eugenol decreased the mRNA expression of *MyHC IIb*. Consistent with our in vivo studies, our in vitro findings again suggested that high doses (200 μM) of eugenol had no effect on muscle fiber type. In summary, our results suggest that eugenol promotes a transformation from fast to slow muscle fiber. However, it should be noted that high doses of eugenol may have no effect on muscle fiber type.

Eugenol promotes oxidative metabolism activity, mitochondrial function, and endurance performance

An increase in the proportion of slow muscle fibers is often accompanied by an increase in skeletal muscle oxidative metabolism activity, mitochondrial function, and endurance performance. Therefore, we examined these indicators in our study. As shown in Figure 2A, EUG50 and EUG100 decreased LDH activity and increased SDH activity in the GAS muscle. In the TA muscle, LDH activity was decreased in all EUG groups, and EUG100 increased the activities of SDH and MDH. Then, we chose 100 mg/kg eugenol (as the optimal dose) for the exhausting swimming test. As shown in Figure 2B, EUG100 increased the exhaustion time of mice. In addition, the transcript levels of mitochondrial transcription factors *PGC-1α*, *NRF1*, and *TFAM* and the mRNA expression of components of the mitochondrial electron transport chain were increased in eugenol-treated mice (Figure 2C). The protein expression of mitochondrial electron transport complex I and complex V was upregulated in eugenol-treated mice (Figure 2D). Furthermore, EUG100 improved the mtDNA copy number in the GAS and TA muscle (Figure 2E), and 12.5-100 μM EUG increased the mtDNA copy number in C2C12 myotubes (Figure 2F).

Eugenol promotes lipolysis and browning of fat

Our research has found that both EUG100 and EUG200 promoted ADF (Figure 3A). However, interestingly, there was no change in body weight (Figure 1A). This indicates that there was an increase in ADF/ADG (Figure 3A). In addition, eugenol decreased iWAT and gWAT weight while promoting BAT weight (Figure 3B). And eugenol decreased T-CHO and LDL while increasing HDL level in serum (Figure 3C). These apparent results suggest that eugenol may increase the energy metabolism rate in mice, offsetting the weight gain and increased fat synthesis resulting from increased food intake. Therefore, we further speculate that eugenol may promote lipolysis and fat thermogenesis. As we speculated, we found that eugenol promoted the mRNA expression of the fat synthesis-related genes *PPARγ* and *HSL*, as well as the fatty acid transport gene *FABP4*, in

iWAT (Figure 3D). In gWAT, it was found that eugenol promoted the mRNA expression of the *FASN* and *FABP4* (Figure 3D). We further examined the mRNA expression of key genes involved in browning of fat, and found that eugenol promoted the mRNA expression of *CD137*, *TBX1*, *UCP-1*, *PRDM16*, *Dio2*, and *Cidea* in iWAT, while eugenol promoted the mRNA expression of *TMEM26*, *UCP-1*, *PRDM16*, *Dio2*, and *Cidea* in gWAT (Figure 3E). At the protein level, eugenol promoted the expression of the fatty acid transport protein FABP-1, as well as the UCP-1 protein expression in gWAT (Figure 3F). In addition, we also examined the effects of eugenol on the browning-related proteins and mitochondrial complex proteins in BAT. It was found that eugenol promoted the UCP-1 and PGC-1α protein expression (Figure 3G), as well as the mitochondrial electron transport complex III and complex V protein expression (Figure 3H). Together, these results indicate that eugenol promotes lipolysis and browning of fat.

Eugenol activates TRPV1-mediated CaN/NFATc1 signaling pathway in skeletal muscle

Based on the gene expression profiling, it was observed that TRPV1 is expressed in all tissues, including adipose and muscle tissues, with the highest expression in skeletal muscle compared to other TRP channels (Figure 4A and Figure 4-figure supplement 1A). qPCR analysis confirmed the expression of TRPV1 and TRPV2 in skeletal muscle, and the mRNA expression of only *TRPV1* was promoted by EUG50 and EUG100 in TA muscle. In C2C12 cells, only TRPV1-4 were expressed, and only *TRPV1* mRNA expression was promoted by 12.5 and 25 μM eugenol (Figure 4C). Adipose tissue expressed TRPV1 and TRPV2 genes, and EUG100 and EUG200 promoted *TRPV1* mRNA expression, while EUG50 promoted T*RPV2* mRNA expression (Figure 4-figure supplement 1B and C). The effect of eugenol on TRPV1 protein expression was consistent with its effect on *TRPV1* mRNA expression in both skeletal muscle tissue and C2C12 cells (Figure 4D-F). Moreover, taking the TRPV1-capsaicin binding sites (TYR511, SER512, THR550, and GLU570) (***Carnevale and Rohacs, 2016***) as the potential binding pocket, molecular docking analysis showed that eugenol bound at the binding pocket and interacted with THR550, ASN551, LEU553, TYR554,

ALA566, ILE569, GLU570, and ILE573 (Figure 4-figure supplement 2). Based on the above results, we conclude that eugenol has the potential to activate TRPV1 in both skeletal muscle and adipose tissue. We further investigated the TRPV1-mediated CaN/NFATc1 signaling pathway in skeletal muscle. CnA is a catalytic subunit of CaN, and its expression level reflects the activity of CaN. Our results showed that EUG50 and EUG100 increased CnA protein expression in the GAS and TA muscles (Figure 4D and 4E), and 12.5-100 μM eugenol promoted CnA protein expression in C2C12 myotubes (Figure 4F). The regulator of calcineurin 1 (MCIP1) is a biomarker to reflect the CaN activity (***Yang et al., 2000***), the mRNA expression of *MCIP1* was increased in EUG100 groups (Figure 4-figure supplement 3). Furthermore, NFATc1 protein expression was promoted by EUG50 and EUG100 in the GAS and TA muscles, and by 12.5-50 μM eugenol in C2C12 myotubes (Figure 4G-I). In summary, our *in vivo* and *in vitro* studies both suggest that eugenol can activate the TRPV1-mediated CaN/NFATc1 signaling pathway in skeletal muscle. Interestingly, similar to the effects of eugenol on muscle fiber types, we again found that high doses of eugenol have no effect on the signaling pathway.

Eugenol promotes fast to slow muscle fiber transformation by activating TRPV1-mediated CaN/NFATc1 signaling pathway

To further investigate the role of TRPV1 in regulating fast to slow muscle fibers, we treated C2C12 myotubes with 25 μM eugenol and either 1 μM TRPV1 inhibitor AMG-517 or 0.5 μM CaN inhibitor cyclosporine A (CsA). The results showed that TRPV1 inhibition weakened the increase in intracellular Ca^{2+} levels induced by eugenol, suggesting that eugenol acts via TRPV1 (Figure 5A). Furthermore, the inhibition of TRPV1 and CaN attenuated the effect of eugenol on CaN and muscle fiber type protein expression (Figure 5B and C). Importantly, immunofluorescence analysis revealed that eugenol increased the fluorescence intensity of slow MyHC, while the inhibition of TRPV1 and CaN eliminated this effect (Figure 5D).

The myokines regulated by CaN

To investigate which myokines are controlled by CaN, C2C12 myotubes were treated with the Ca^{2+} ionophore A23187. As shown in Figure 6A-C, A23187 increased the mRNA expression of *MCIP1*, the protein expression of CnA, and CaN activity. We chose 0.5 μM A23187 for subsequent experiments and confirmed that it increased intracellular Ca^{2+} levels (Figure 6D). To identify CaN-controlled myokines, we next detected the mRNA expression of several myokines that have been well documented to improve metabolic homeostasis (***Eckel, 2019; Whitham and Febbraio, 2016***) and promote fast to slow muscle fiber transformation (***Correia et al., 2021; Knudsen et al., 2020; Men et al., 2021; Quinn et al., 2013***) (Table1). As shown in Figure 6E, A23187 significantly increased the mRNA expression of *FNDC5*, *IL-6*, *IL-15*, and *Metrnl*. However, *IL-13* mRNA expression was not detected in C2C12 myotubes. In addition, a correlation heatmap showed the highest correlation coefficient (R=0.954) between MCIP1 expression and IL-15 expression, followed by MCIP1 and IL-6 (R=0.846), MCIP1 and Metrnl (0.77), and MCIP1 and FNDC5 (0.651) (Figure 6F). Furthermore, a TFBS prediction revealed more potential binding sites between the IL-15 promoter and NFATc1 (Figure 6G). Based on the correlation and TFBS analysis, it was suggested that IL-15 is the myokine most likely to be regulated by the CaN/NFATc1 signaling pathway, and we selected it for further study.

The myokine IL-15 expression depends on CaN/NFATc1 signaling pathway

Firstly, it was observed that treatment with 0.5 and 1 μM Ca^{2+} ionophore led to upregulation of IL-15 protein expression (Figure 7A). Subsequently, we treated C2C12 myotubes with 0.5 μM Ca^{2+} ionophore and 0.5 μM CsA to investigate their effects. We found that Ca^{2+} ionophore treatment upregulated the expression of CnA, NFATc1, and IL-15 proteins, while inhibition of CaN eliminated these effects (Figure 7B-D). Furthermore, Ca^{2+} ionophore treatment increased the expression of slow MyHC and decreased the expresssion of fast MyHC, while CsA blocked this effect (Figure 7-figure supplement 1). Based on the transcription factor motif databases (JASPAR and hIFtarget), it was predicted that a sequence (5’-AATGGAAAA-3’) in the promoter regions of

IL-15 was a potential binding site of NFATc1 (Figure 7E), and DNA-protein docking analysis also revealed a high probability of binding between this sequence and the NFATc1 protein (Figure 7F). We then performed an EMSA assay to validate the binding of NFATc1 to this sequence. The probes used in the EMSA assay were shown in Figure 7G and the EMSA results were shown in Figure 7H. We observed upward migration bands when the C2C12 nuclear protein extract (NE) was incubated with the bio-NFATc1 probe (lanes 2-4), and compared to the control (lane 2) and CsA inhibition group (lane 4), Ca^{2+} treatment group showed higher expression of the band (lane 3). Moreover, the use of competing cold-NFATc1 probes showed no upward migration band (lane 5), while using the mut-NFATc1 probe again showed the band (lane 6). These findings suggest that NFATc1 may bind to the promoter of IL-15. We further investigated whether NFATc1 transcriptionally activates IL-15 through luciferase reporter assays. As shown in Figure 7I, overexpression of NFATc1 promoted NFATc1 protein expression in HEK293T cells. Additionally, after transfection with the IL-15 reporter plasmid, overexpression of NFATc1 enhanced the relative fluorescence intensity (Figure 7J), suggesting that the transcriptional activation of IL-15 is regulated by NFATc1.

Eugenol promotes IL-15 level by TRPV1-mediated CaN/NFATc1 signaling pathway

We conducted further experiments to examine the effect of eugenol on IL-15 expression. Our results (Figure 8A-C) showed that EUG50 and EUG100 promoted the mRNA and protein expression of IL-15 in both GAS and TA muscle. Interestingly, in EDL and SOL muscle, which are dominated by fast and slow muscle fibers respectively, EUG100 promoted IL-15 mRNA expression (Figure 8D). We also found that the mRNA expression of IL-15 was higher in SOL muscle than in EDL muscle (Figure 8D). Moreover, Pearson's correlation analysis showed that IL-15 expression positively correlated with MyHC I (R=0.714) and MyHC IIa (R=0.774) expression, and negatively correlated with MyHC IIb (R=-0.568) (Figure 8D). Consistent with the mRNA expression data, the IL-15 protein expression was also higher in SOL muscle than in EDL muscle (Figure 8E). Additionally, EUG50 and EUG100 increased the concentration of IL-15 in the serum

(Figure 8F). These findings suggested that IL-15 was a slow muscle fiber type-specific myokine that was promoted by eugenol. Our in vitro experiments showed that 25 and 50 μM eugenol increased the mRNA expression and secretion of IL-15 (Figure 9A and B), which was consistent with our in vivo experiments. In addition, the inhibition of TRPV1 and CaN decreased the upregulation of eugenol on IL-15 mRNA and protein expression (Figure 9C and D). Immunofluorescence staining with IL-15 also showed similar results (Figure 9-figure supplement 1).

Discussion

Our study reveals that eugenol can serve as an exercise mimetic that promotes remodeling of skeletal muscle fibers and expression of the myokine IL-15 through the TRPV1-mediated CaN/NFATc1 signaling pathway. This expands the traditional biological functions of eugenol and provides a theoretical basis for its potential applications in the food and drug industry. Moreover, we identify a novel TRPV1-mediated CaN/NFATc1 signaling pathway that promotes the transformation of fast to slow muscle fibers. Importantly, we provide the first explanation of the mechanism underlying the release of the myokine IL-15.

TRPV1, like all other TRP channels, assembles as tetramers to form cation-permeable pores (***Clapham, 2003***). Initially identified as a capsaicin receptor and heat-activated ion channel that modulates pain and neurogenic inflammation (***Caterina et al., 1997***), subsequent studies have found that TRPV1 is expressed on many non-neural sites and plays roles in immunity, vasculature, obesity, and thermogenesis (***Fernandes et al., 2012***). Previous studies have also shown that capsaicin activated TRPV1 to improve endurance capacity and energy metabolism (***Luo et al., 2012***), counter obesity (***Baskaran et al., 2016***), and intervene diabetes (***Wang et al., 2012***). Therefore, TRPV1 is a strong target for the discovery of exercise mimetics, which drove us to search for TRPV1 agonists that may act as exercise mimetics. We focused on eugenol, a healthy and edible plant extract that may be a potential TRPV1 agonist. Since eugenol contains a vanilloyl fragment, it is possible to

bind TRPV1 through a similar pattern to capsaicin. Indeed, previous studies have found that eugenol activates TRPV1 in a heterologous expression system and rat trigeminal ganglion neurons (***Xu et al., 2006; Yang et al., 2003***), and a recent study reported that 50 and 100 μM eugenol promoted TRPV1 expression in C2C12 myotubes (***Jiang et al., 2022***). In our study, we investigated the mRNA expression profile of TRP channels in C2C12 myotubes and skeletal muscle, and found that only TRPV1 mRNA was upregulated in response to eugenol treatment. Moreover, it was observed that the protein expression of TRPV1 was consistent with the mRNA expression. Our molecular docking results also indicated that eugenol bound to the capsaicin binding pockets of TRPV1. Based on these findings, we propose that eugenol specifically activates TRPV1 in skeletal muscle, rather than other TRP channels. This may be due to the relatively higher expression of TRPV1 in skeletal muscle compared to other TRP channels.

One of the benefits of exercise mimetics for body is to promote the skeletal muscle oxidative phenotype and endurance performance (***Fan and Evans, 2017***). Our studies showed that eugenol improved endurance performance and promoted fast-to-slow muscle fiber transformation. Slow muscle fibers are characterized by the improvement in mitochondrial function and oxidative metabolism (***Choi and Kim, 2009***). As expected, eugenol also promoted mitochondrial function and oxidative metabolism capacity in skeletal muscle. In a previous study, capsaicin-induced TRPV1 activation was shown to promote exercise endurance and the skeletal muscle oxidative phenotype (***Wang et al., 2012***). The authors suggested that TRPV1 activated calmodulin-dependent protein kinase (CaMK) by increasing intracellular Ca^{2+}, and the activation of CaMK further activated PGC-1α, contributing to these effects (***Wang et al., 2012***). In skeletal muscle, the CaN signaling pathway is also an important Ca^{2+}-mediated signal that promotes the muscle oxidative phenotype (***Sakuma and Yamaguchi, 2010***). CaN induces the translocation of NFATc1 to the nucleus by dephosphorylating NFATc1, thereby switching fast to slow muscle fibers (***Calabria et al., 2009***). TRPV1 activation has been shown to promote CaN activity in several other cells and

tissues (***Hou et al., 2019; Ma et al., 2011; Yang et al., 2018***), but the link between TRPV1 and CaN signaling in skeletal muscle has not yet been established, nor has it been determined whether TRPV1 promotes muscle oxidative phenotype through the CaN/NFATc1 signaling pathway. Therefore, we investigated the role of TRPV1-mediated CaN signaling pathway in the regulation of muscle fiber types. We found that eugenol increased CaN expression through the activation of TRPV1, and that it promoted fast-to-slow muscle fiber transformation via the TRPV1-mediated CaN/NFATc1 signaling pathway. Recent studies have also found that eugenol increases muscle glucose uptake through the TRPV1/CaMK signaling pathway (***Jiang et al., 2022***), suggesting that both CaN and CaMK signaling may be involved in TRPV1-facilitated skeletal muscle oxidative phenotype.

Another benefit of exercise mimetics is the alleviation of obesity and improvement of metabolic health. It has been reported that an increase in slow-twitch fiber content is positively associated with reduced obesity and improved metabolic health (***Carlson et al., 2010***). Previous studies have shown that eugenol can reduce blood lipids in rats with hyperlipidemia (***Harb et al., 2019***), lower blood glucose and insulin resistance in diabetic mice (***Al-Trad et al., 2019; Sanae et al., 2014***), and reduce hepatic lipid accumulation in high-fat-fed mice (***Rodrigues et al., 2022***), demonstrating its potential in improving glucose and lipid metabolism. In our study, we found that feeding eugenol under standard diet conditions may promote fat thermogenesis and browning to facilitate fat breakdown. Interestingly, it was found that capsaicin alleviated obesity and promoted white fat browning by activating the TRPV1 (***Baskaran et al., 2016***). Our study found that eugenol promoted TRPV1 mRNA expression in adipose tissue, indicating that eugenol may promote white fat browning through TRPV1 activation.

Exercise mimetics may exert beneficial effects on the body by promoting the release of myokines (***Fan and Evans, 2017***). Some myokines, such as IL-13 (***Knudsen et al., 2020***), IL-15 (***Quinn et al., 2013***), and neurturin (***Correia et al., 2021***), have been well documented to improve

metabolic homeostasis, promote fast to slow muscle fiber transformation, and improve endurance capacity. However, the regulatory mechanisms for myokines expression are largely unclear. Since myokines are usually promoted by muscle contraction, and Ca^{2+} is the main signal in muscle contraction, CaN, downstream of Ca^{2+}, has been considered to regulate myokine expression. CaN has been reported to regulate the expression of myokine IL-6 (***Banzet et al., 2005; Banzet et al., 2007***). Additionally, the transcriptional activation activity of myokines IL-4 and IL-13 is thought to be promoted by transcription factor NFATc2, which is downstream of CaN (***Jacquemin et al., 2007; Zádor, 2008***). Based on the correlation and TFBS analysis, it was found that IL-15 is most likely to be regulated by the CaN/NFATc1 signaling pathway in our study. IL-15 has been reported as a myokine that improves fatty acid utilization, insulin sensitivity, and endurance capacity, and prevents obesity and diabetes (***Nadeau and Aguer, 2019***). In different cell models, CsA-mediated inhibition of CaN decreased the release of IL-15 (***Cho et al., 2002; Cho et al., 2007***). Furthermore, an increase in CaN expression in 3T3-L1 cells was accompanied by an increase in IL-15 expression (***Almendro et al., 2009***). Our study found that the CaN/NFATc1 signaling pathway contributes to the eugenol-promoted expression of IL-15. Furthermore, we observed that the expression of IL-15 was higher in the slow-twitch SOL muscle than in the fast-twitch EDL muscle, suggesting that an increase in muscle oxidative phenotype may further promote the release of IL-15. However, the mechanism underlying how IL-15 promotes the muscle oxidative phenotype remains unclear and requires further investigation.

Apparently, an interesting finding throughout our *in vitro* and *in vivo* study was that the high doses of eugenol (200 mg/kg for mice and 200 μM eugenol for C2C12 myotubes) had no effect on TRPV1-mediated CaN/NFATc1 signaling pathway, IL-15 expression, and muscle fiber type. We suspected that high doses of eugenol may cause desensitization of TRPV1 in skeletal muscle under our study conditions. This indirectly verified that the activation of TRPV1 does promote IL-15 expression and fast-to-slow muscle fiber transformation type. It is well-known that continuous

activation of TRPV1 by capsaicin causes TRPV1 desensitization, which is considered to underlie the analgesic effects of capsaicin (***Koplas et al., 1997***). As previously reported, TRPV1 agonists promoted TRPV1 desensitization in a dose- and time-dependent manner by targeting lysosomes to degrade TRPV1 in HEK293 cells (***Sanz-Salvador et al., 2012***). A hypothetical model suggested that upon TRPV1 opening to allow Ca^{2+} influx, Ca^{2+}/CaM binds to the CaM-binding domain of TRPV1, leading to channel inactivation, and CaN dephosphorylates TRPV1 to desensitize TRPV1 (***Hasan and Zhang, 2018***). However, most results on TRPV1 desensitization were obtained by capsaicin treatment of cells, and it is unknown whether high-dose eugenol promotes TRPV1 desensitization through a similar mechanism. Therefore, it is essential to select the appropriate dose of eugenol for the application of TRPV1 activators.

In conclusion, our findings indicate that eugenol can promote the transformation of fast to slow muscle fibers and induce the myokine IL-15 expression through the TRPV1-mediated CaN/NFATc1 signaling pathway. Moreover, our study is the first to demonstrate that the expression of IL-15 is regulated by the CaN/NFATc1 signaling pathway. These results suggest that eugenol may have potential as a novel exercise mimetic and that TRPV1 may represent a promising therapeutic target for metabolic disorders.

Methods and Materials

Animals, treatments, and sample collection

A total of eighty 4-week-old male C57BL/6J mice (Dashuo Experimental Animal Co.Ltd., Chengdu, China) were divided into four treatments (n = 12) using a simple randomization method. The control group were fed a basal diet supplemented with 0% eugenol (EUG, purity≥98%, Sigma, St. Louis, MO, USA), other groups were fed a basal diet supplemented with 50, 100 and 200 mg/kg eugenol, respectively (EUG50, EUG100 and EUG200). All mice were housed in individual cages (23°C ± 2°C, 12-h light/12-h dark cycle) and provided with free access to feed and water. The experiment lasted for 4 weeks. The weight of mice was measured every week. At the end of the

experiment, mice anesthetized with CO_2 were sacrificed. After being weighed and photographed, skeletal muscle [including tibialisanterior (TA), gastrocnemius (GAS), soleus (SOL), and extensor digitorum longus (EDL)], fat [including inguinal white adipose tissue (iWAT), gonadal white adipose tissue (gWAT), brown adipose tissue (BAT)] were collected and stored at -80 °C for subsequent analyses. All procedures of animal experiments were performed according to protocols approved the Animal Care Advisory Committee of Sichuan Agricultural University under permit No. YYS20200929.

Exhausting swimming test

The forced swimming capacity test was employed in this study to evaluate the effects of eugenol on endurance capacity in mice. A total of thirty 4-week-old mice were divided into the control and EUG100 group (n=15). After four weeks of feeding, the mice with a load of lead wire (7% of body weight) attached to its tail were placed in individual swimming pools (25 ± 1°C, 35-cm depth). Exhaustive swimming time was immediately recorded when the mice failed to return to the surface continuously over a 7-second time frame and showed a lack of coordinated movements.

Cell culture and treatments

C2C12 cells (Shanghai Cell Bank, Chinese Academy of Sciences, passages 3-8) were cultured in Dulbecco modified Eagle medium (DMEM) (Invitrogen, Carlsbad, CA, USA) supplemented with 10% fetal bovine serum (Gibco, Paisley, Scotland, UK), 100 mg/L streptomycin and 100 U/ml penicillin (Gibco) at 37°C in a 5 % CO2 atmosphere. When cells reached ~80% confluence, 2% horse serum (Gibco) replaced 10% fetal bovine serum to induce differentiation. For eugenol treatment, cells were treated with 0, 12.5, 25, 50, 100, 200 μM EUG for 1 day after 4 days of differentiation. For Ca^{2+} ionophore A23187 (Sigma) treatment, cells were treated with 0, 0.1, 0.5, 1 μM A23187 for 16 h after 2 days of differentiation, or cells were treated with 0.5 μM A23187 and 0.5 μM CsA. For the following mechanism studies, cells were treated with 25 μM EUG and 1 μM TRPV1 inhibitor AMG-517 or 0.5 μM CaN inhibitor cyclosporin A (CsA, Sigma).

Cell viability assay

Cell viability was analyzed using Cell-Counting Kit-8 (Beyotime, Jiangsu, China) to determine the safe dose of EUG on C2C12 myotubes. Briefly, cells were treated with EUG (0, 12.5, 25, 50, 100, 200, 400, 800, 1600 μM) for 1 day after 4 days of differentiation, 10 μL CCK-8 solution was then added to each well and then incubated for 1 h at 37 ℃. After incubation, the OD value was immediately measured at 450 nm using the SpectraMax 190 Absorbance Plate Reader.

Measurement of intracellular calcium ion (Ca^{2+})

After 1 day of treatment with C2C12 myotubes in 24-well cell culture plates, the cells were digested using Trypsin-EDTA solution and transferred from each well into a centrifuge tube. The Trypsin-EDTA solution was removed and the cells were washed 3 times with a calcium-free PBS solution. Following this, the PBS solution was removed and 200 μL of 5 μM Ca^{2+} fluorescent probe Fluo-4 (Beyotime) was added to the cells and incubated at 37°C for 30 minutes. After the incubation, the probe was removed by washing the cells 3 times with PBS. Finally, Ca^{2+} fluorescence was detected using flow cytometry (FACSVerse, BD Biosciences, East Rutherford, NJ, USA) and analyzed using FlowJo 10.0.7 software.

Gene expression and mitochondrial DNA quantitative PCR (qPCR)

Total RNA was extracted using RNA isolater Total RNA Extraction Reagent (Vazyme, Nanjing, China) and genomic DNA was extracted using mammalian genomic DNA extraction kit (Beyotime) according to the instructions. After measuring the concentration of total RNA, total RNA reverse transcribed to cDNA using HiScript II Q RT Supermix (Vazyme). qPCR was performed using ChamQ SYBR Color qPCR Master Mix (Vazyme) on a 7900 HT Real-time PCR system (384-cell standard block) (Applied Biosystems). Relative mtDNA was quantified by qPCR using primers for mitochondrially-encoded *Nd1* normalized to nuclear-encoded *36B4 (Rplp0)* DNA. And *GAPDH* was used as an endogenous control for normal qPCR. The primer sequences are listed in Appendix

1—table 1.

Protein extraction and Western Blot

RIPA lysis buffer (Beyotime) was used to extract total protein. The nuclear protein was extracted using NE-PER Nuclear and Cytoplasmic Extraction Reagents (ThermoFisher). Protein from conditioned media was extracted using methanol-choloroform precipitation method as previous (***Jakobs et al., 2013***). Protein concentration was determined by the BCA assays, and then proteins were transferred to a nitrocellulose membrane using a wet Trans-Blot system (Bio-Rad, Hercules, CA, USA). The primary antibodies used were anti-slow MyHC (Sigma, cat. no. M8421), anti-fast MyHC (Sigma, cat. no. M4276), anti-TRPV1 (Alomone, cat. no. ACC030), anti-Calcineurin A (CnA, abcam, cat. no. ab90540), anti-NFATc1 (Cell Signaling Technology, cat. no. #8032), anti-IL-15 (R&D system, cat. no. AF447), anti-PGC-1α (Proteintech, cat. no. 66369-1-Ig). anti-NDUFA9 (GeneTex, cat. no. GTX132978), anti-SDHA (GeneTex, cat. no. GTX636098), anti-UQCRC1 (GeneTex, cat. no. GTX630393), anti-MTCO1(Bioss, cat. no. bs-3953R), anti-ATP5B (GeneTex, cat. no. GTX132925), anti-FABP1 (Cell Signaling Technology, cat. no. #13368), anti-UCP-1 (Proteintech, Cat. no. 23673-1-AP), anti-PRDM16 (R&D system, cat. no. AF6295), anti-β-actin (TransGen, cat. no. HC201-01), and anti-Histone H3 (Beyotime, cat. no. AF0009). Coomassie staining is depicted as loading control for conditioned media protein (***Welinder and Ekblad, 2011***). The signal was visualized using a Clarity Western ECL Substrate (BioRad, Hercules, CA, USA) and a ChemiDoc XRS Imager System (BioRad). The target band density was identified using Image Lab 5.1 (BioRad).

Immunofluorescence (IF)

After treatment, C2C12 myotubes were washed three times (5 min each time) with phosphate-buffered saline (PBS) and fixed in Immunol Staining Fix Solution (Beyotime) for 20 min. Then C2C12 myotubes were permeabilized with 0.5% Triton X-100 for 20 min, blocked with blocking buffer for 2 hours at 37 °C, incubated with the primary antibodies including slow MyHC (1:50,

Sigma, Cat. No. M8421) for 16 hours, and incubated with the fluorescent secondary antibody (1:1000, Cell Signaling, USA) for 2 hours at 37 ℃. Finally, 4,6-diamidino-2-phenylindole (DAPI) (Beyotime) was used to stain cell nucleus for 10 minutes at room temperature. A positive signal was detected and captured using fluorescence microscopy (Lecia DMI4000 B).

Molecular-protein docking and DNA-protein docking

The protein structures of TRPV1 (PDB codes: 5IS0) and NFATc1 (PDB codes: 1A66) were downloaded from the Research Collaboratory for Structural Bioinformatics Protein Data Bank database (RCSB PDB, https ://www.rcsb.org/) (***Burley et al., 2019***). The structure of eugenol (ZINC1411) was downloaded from the ZINC database (https://zinc.docking.org/substances/). The DNA structure was generated using Discovery Studio 2019 software (Discovery Studio 2019; BIOVIA; San Diego, USA). Discovery studio 2019 software was used to perform molecular-protein docking. HDOCK (http://hdock.phys.hust.edu.cn/) was used to perform DNA-protein docking.

Prediction of transcription factors binding sites (TFBS)

The gene promoter sequences of mouse (upstream 2 kb) were acquired from National Center for Biotechnology Information. hIFtarget (http://bioinfo.life.hust.edu.cn/hTFtarget#!/) and JASPAR (http://jaspar.ge-nereg.net/) applied to predict the potential NFATc1 binding sites at the promoter of genes. A putative binding sites predicted by both two tools were selected for further electrophoretic mobility shift (EMSA) probes design.

Electrophoretic mobility shift assay (EMSA)

After synthesizing the single-stranded probes for EMSA, annealing buffer for DNA oligos (5x) (Beyotime) was used to anneal to form double-stranded DNA probes. EMSA assay were performed using chemiluminescent EMSA Kit (Beyotime) according to the instructions. Briefly, 10 μL reaction system with nuclease-free water, EMSA/Gel-Shift Binding Buffer, nuclear protein, and probe was transferred to a nitrocellulose membrane using a wet Trans-Blot system. The reaction

system includes negative control reaction (no nuclear protein), sample reaction, probe cold competition reaction (100-fold unlabeled probe), mutation probe cold competition reaction (100-fold unlabeled mutation probe). The signal was visualized using a Clarity Western ECL Substrate (BioRad, Hercules, CA, USA) and a ChemiDoc XRS Imager System (BioRad).

Plasmid construction and extraction

The plasmid of pcDNA3.1 vector, pCDNA3.1-NFATc1 (The NFATc1 coding sequences were inserted into the pcDNA3.1 vector), pGL3 vector, and pGL3-IL15 (The sequence of 2 kb upstream of the IL-15 promoter sequence were inserted into the pGL3 vector) were from Tsingke Biotechnology Co., Ltd (Beijing, China). Plasmid amplification is provided in *Escherichia coli* bacteria cells. Plasmid Maxi Preparation Kit for All Purpose (Beyotime) was used to extract plasmids.

Dual-luciferase reporter gene assay

HEK293T cells in 48-well plates were transfected with pcDNA3.1 together with pGL3 or pcDNA3.1-NFATc1 together with pGL3 or pcDNA3.1 together with pGL3-IL15 or pcDNA3.1-NFATC1 together with pGL3-IL15. Luciferase activity was detected by a Dual-Luciferase assay kit (Beyotime) with Glomax 96 microplate luminometer (Promega) in luminometer mode. The raw values of firefly luciferase were normalized to Renilla luciferase.

Enzyme activities analysis

The tissue and C2C12 myotube were homogenized in saline and centrifuged at 3500 × g 4 ℃ for 10 minutes. The supernatant was carefully transferred to a centrifuge tube. Total protein concentration was determined by the BCA assays. The enzyme activity of lactate dehydrogenase (LDH), malate dehydrogenase (MDH), succinic dehydrogenase (SDH), and CaN were measured using commercial assay kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China).

Statistical analyses

SAS 9.4 software was used to perform one-way ANOVA and t test. After the normality and homogeneity test, one-way ANOVA followed by Duncan's multiple range test was performed for multiple-groups comparisons. Student's t test was performed for two-groups comparisons. Correlation analysis was performed by Pearson's correlation coefficient analysis. Statistical methods were not used to predetermine sample size. GraphPad Prism 8.0 (GraphPad Software, Inc., San Diego, CA) software was used to draw column charts and Omicstudio tools (https://www.omicstudio.cn/tool.) was used to draw heatmaps. Data were expressed as mean ± SEM. Statistical significance was defined as $^{\#}P < 0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ for all figures.

Author contributions

Tengteng Huang: Investigation, Data curation, Formal analysis, Writing - original draft. Xiaoling Chen: Conceptualization, Methodology, Project administration, Supervision. Jun He: Methodology. Ping Zheng: Methodology. Yuheng Luo: Methodology. Aimin Wu: Methodology. Hui Yan: Methodology. Bing Yu: Methodology. Daiwen Chen: Methodology. Zhiqing Huang: Conceptualization, Funding acquisition, Methodology, Supervision, Writing - review & editing

Competing interests

The authors declare no competing interest.

Data availability

Data will be made available on request.

Funding

This work was supported by the National Key R&D Program of China (No. 2022YFF1000100), the Natural Science Foundation of Sichuan Province (No. 2023NSFSC0238), and the Sichuan Science and Technology Program (No. 2021ZDZX0009).

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Figures and Tables

Table 1 Myokines to be tested in our study.

	Myokines	References
Myokines that improve metabolic homeostasis	CX3CL1, FGF21, FNDC5, IL-6, IL-8, IL-15	***(Whitham, M., and Febbraio, M.A, 2016)***
	Metrnl, FGF21, FNDC5, Myonectin	(***Eckel, 2019***)
Myokines that improve endurace capacity and promote fast to slow muscle fiber transformation	FNDC5	***(Men et al., 2021)***
	IL-13	(***Knudsen et al., 2020***)
	IL-15	(***Quinn et al., 2013***)
	Neurturin	(***Correia et al., 2021***)

Figure captions

Figure 1. Eugenol promotes the transformation of fast to slow musle fiber. (A) The body weight of the mice. (**B, C)**, Skeletal muscle weight and representative images of skeletal muscle. **(D-F)** The protein expression of muscle fiber type in GAS and TA muscle and in C2C12 myotubes. (**G-H)** The mRNA expression of muscle fiber type in GAS and TA muscle and in C2C12 myotubes. For A-B, N=12 per group. For D-E, N=3 per group. For F and H, N=4 per group. For G, N=6 per group. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 1-figure supplement 1. Effect of eugenol on C2C12 cell viability. Cells were treated with 0, 12.5, 25, 50, 100, 200 μM EUG for 1 day after 4 days of differentiation. The C2C12 cell viability was measured using CCK-8 kit. N=6 per group. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 2. Eugenol promotes oxidative metabolism activity, mitochondrial function, and endurance performance of mice. (A) The effect of eugenol on metabolism enzymes activity in GAS and TA muscle. **(B)** The effect of eugenol on exhausting swimming time in mice. (**C)** The heatmap for the mRNA expression of genes encoding mitochondrial complex components and transcription factors controling mitochondrial biogenesis in GAS muscle. Color gradient represents relative mRNA expression with darker colors indicating higher expression. **(D)** Protein expression of mitochondrial electron transport complexes in GAS muscle. Complex I (NDUFA1), complex II (SDHA), complex III (UQCRC1), complex IV (MTCO1), and comlex V (ATP5B). (**E, F)** mtDNA copy number in muscles and cells. For A, N=6 per group. For B, N=15 per group. For C and F, N=4 per group. For D, N=3 per group. For E, N=6 per group. $^{\#}P<0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 3. Eugenol enhances lipolysis and thermogenesis. (**A)** The ADF and the ration of ADF to ADG. (**B)** Tissue weight of adipose weight. (**C)** The level of T-CHO, LDL, and HDL in serum. (**D)** The mRNA expression of genes related to lipolysis, lipogenesis, and lipid transport in iWAT

and gWAT. (**E)** The mRNA expression of genes related to adipose browning and thermogenesis in iWAT and gWAT. (**F)** The protein expression of FABP1 and UCP1 in iWAT and gWAT. (**G)** The expression of protein related to adipose browning and thermogenesis in BAT. (**H)** The protein expression of mitochondrial electron transport complexes in BAT. For A-B, N=12 per group. For C-E, N=6 per group. For F-H, N=3 per group. $^{\#}P<0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 4. Eugenol activated TRPV1-mediated CaN/NFATc1 signaling pathway. (**A)** The gene expression profile of TRP channels in skeletal muscle was obtained from the GTEx dataset in The Human Protein Atlas (https://www.proteinatlas.org/). (**B, C)** The mRNA expression of TRP channels in TA muscle and C2C12 myotubes. (**D-F)** The TRPV1 and CnA protein expression in GAS and TA muscle and in C2C12 myotubes. (**G-I)** The protein expression of NFATc1 in GAS and TA muscle and in C2C12 myotubes. For B, N=6 per group. For C, F, and I, N=4 per group. For D-E and G-H, N=3 per group. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 4-figure supplement 1. TRP channels expression profiles and *TRPV1* mRNA eexpression in adipose tissue. The gene expression profile was obtained from the GTEx dataset in The Human Protein Atlas (https://www.proteinatlas.org/). (**A)** TRPV1 expression profiles in tissues. (**B)** TRP channels expression profiles in adipose tissue. (**C)** The mRNA expression of TRP channels in adipose tissue. For C, N=6 per group. $^{\#}P<0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 4-figure supplement 2. Molecular docking for eugenol and TRPV1. The capsaicin binding sites (TYR511, SER512, THR550, and GLU570) were selected as the binding pocket. The figure showed TRPV1 amino acid residues interacting with eugenol and the intermolecular force.

Figure 4-figure supplement 3. The mRNA expression of *MCIP1*. N=6 per group. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$.

Figure 5. Eugenol promotes fast to slow muscle fiber transformation by activating TRPV1-mediated CaN/NFATc1 signaling pathway. C2C12 myotubes were treated by 25 μM eugenol and

1 μM TRPV1 inhibitor AMG-517 or 0.5 μM CaN inhibitor CsA for 1 day after 4 days of differentiation. (**A)** The flow cytometry assay was used to detect Ca^{2+} levels in C2C12 myotubes; FITC means the fluo-4 fluorescence and SSC means side scatter. (**B, C)** Western blot was uesd to detect CnA, slow MyHC, and fast MyHC protein expression in C2C12 myotubes. (**D)** Representative immunofluorescence images of Slow MyHC (Green fluorescence). Magnification: × 200. For A-D, N=4 per group. *P < 0.05, **P < 0.01, and ***P < 0.001.

Figure 6. The myokines controlled by CaN. C2C12 myotubes were treated for 16 h with 0, 0.1, 0.5, and 1 μM Ca^{2+} ionophore after 2 days of differentiation. (**A)** The mRNA expression of *MCIP1*. (**B)** The protein expression of CnA. (**C)** The enzyme activity of CaN. (**D)** Fluo-4 was used to stain the Ca^{2+} and the flow cytometry assay was used to detect Ca^{2+} fluorescence in C2C12 myotubes in control and 0.5 μM A23187 groups. (**E)** The heatmap for the myokines mRNA expression in control and 0.5 μM A23187 groups. Color gradient represents relative mRNA expression with darker colors indicating higher expression. **(F)** Correlation analysis of gene expression values of myokines and MCIP1 gene performed by linear regression with Pearson's correlation coefficient (r). Color gradient represents correlation coefficient with darker colors indicating higher positive correlation. (**G)** The number of binding sites for transcription factors NFATc1 were predicted by hTFtarget and JASPAR. For A, N=6 per group. For B-D, N=3 per group. For E, N=4 per group. *P < 0.05, **P < 0.01, and ***P < 0.001.

Figure 7. The myokine IL-15 expression depends on CaN/NFATc1 signaling pathway. (A) C2C12 myotubes were treated for 16 h with 0, 0.1, 0.5, and 1 μM Ca^{2+} ionophore after 2 days of differentiation. The protein expression of IL-15. (**B-D)** C2C12 myotubes were treated by 0.5 μM A23187 and 0.5 μM CsA for 16 h after 2 days of differentiation. The protein expression of CnA, NFATc1, and IL-15. **(E)** Sequence logo of NFATc1 motif and the predicted NFATc1 binding sites in the promoter region of IL-15. **(F)** NFATc1 and the key sequence of IL-15 (5'-AATGAAAA-3') docking. Confidence scores above 0.7 indicate high probability of binding, scores between 0.5 and

0.7 suggest possible binding, and scores below 0.5 indicate unlikely binding. (**G)** The probe sequence of NFATc1. The underline represents the predicted binding site of NFATc1, bio-NFATc1 means oligonucleotide probes that labeled with biotin at the 5' end, cold-NFATc1 means oligonucleotide probes that did not labeled with biotin, mu-NFATc1 means oligonucleotide probes that was mutated at the binding site. (**H)** Nuclear protein extracts (NE) with NFATc1 probe were used to EMSA assay. (**I)** The protein expression of NFATc1 after transfecting 1 μg/mL pcDNA3.1 vector, 0.5 μg/mL or 1 μg/mL pcDNA3.1-NFATc1 in HEK293T cells. (**J)** The relative luciferase intensity referred to the ratio between firefly luciferase intensity and renilla luciferase intensity. For A-D, N=3 per group. For H, N=6 per group. *P < 0.05, **P < 0.01, and ***P < 0.001.

Figure 7-figure supplement 1. Ca^{2+} ionophore A23187 promotes the transformation of fast to slow muscle fiber by CaN signaling pathway. A-C The mRNA and protein expression of muscle fiber type in C2C12 myotubes. For B, N=4 per group. For A and C, N=3 per group. *P < 0.05, **P < 0.01, and ***P < 0.001.

Figure 8. Eugenol promotes the expression and secretion of IL-15 in skeletal muscle of mice. (**A)** The *IL-15* mRNA expression in GAS and TA muscle. **(B, C)** The IL-15 protein expression in GAS and TA muscle. (**D)** Left: The mRNA expression of *MyHC I*, *MyHC IIa*, *MyHC IIb* and *IL-15* in EDL and SOL muscle of mice. Right: Correlation analysis of gene expression values performed by linear regression with Pearson's correlation coefficient (r). Color gradient represents correlation coefficient with darker colors indicating higher positive correlation. (**E)** The protein expreesion of slow MyHC, fast MyHC, and IL-15. (**F)** The concertration of IL-15 in serum. For A, D, and F, N=6 per group. For B-C and E, N=3 per group. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

Figure 9. Eugenol promotes IL-15 level through TRPV1-mediated CaN/NFATc1 signaling pathway. C2C12 myotubes were treated by 0-200 eugenol for 1 day after 4 days of differentiation. (**A)** The effect of eugenol on *IL-15* mRNA expression in C2C12 myotubes. (**B)** The effect of eugenol on IL-15 protein expression in the C2C12 cell medium. Coomassie staining as loading control. **(C, D)** C2C12 myotubes were treated by 25 μM eugenol and 1 μM TRPV1 inhibitor AMG-517 or 0.5 μM CaN inhibitor CsA for 1 day after 4 days of differentiation. The mRNA and protein expression of IL-15. N=4 per group. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

Figure 9-figure supplement 1. Representative immunofluorescence images of IL-15. IL-15 (Green fluorescence) and DAPI (Blue fluorescence). Magnification: × 200.

Source data files

Figure 1-Source Data 1. Western blot raw image.

Figure 2-Source Data 1. Western blot raw image.

Figure 3-Source Data 1. Western blot raw image.

Figure 4-Source Data 1. Western blot raw image.

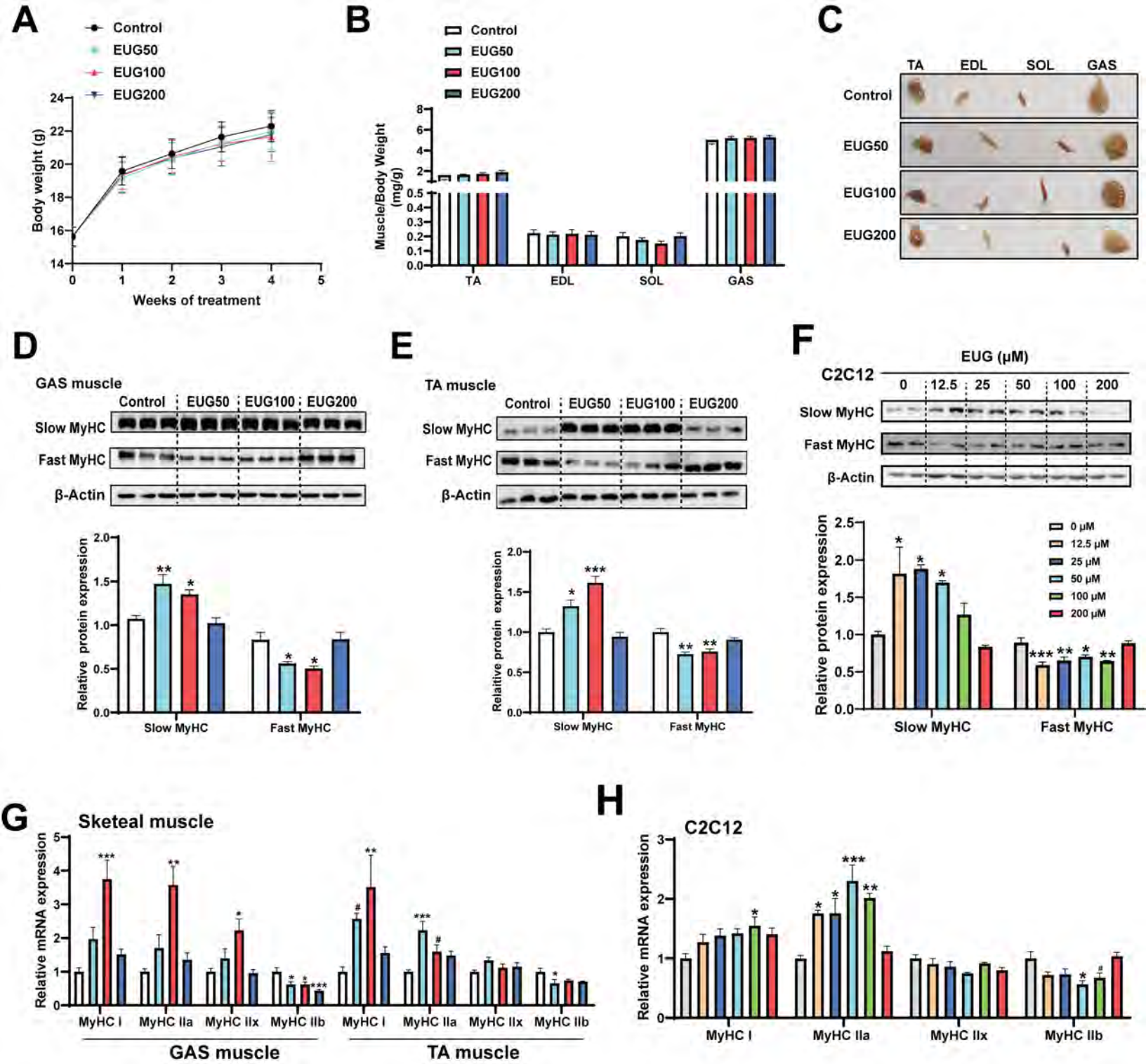
Figure 5-Source Data 1. Western blot raw image.

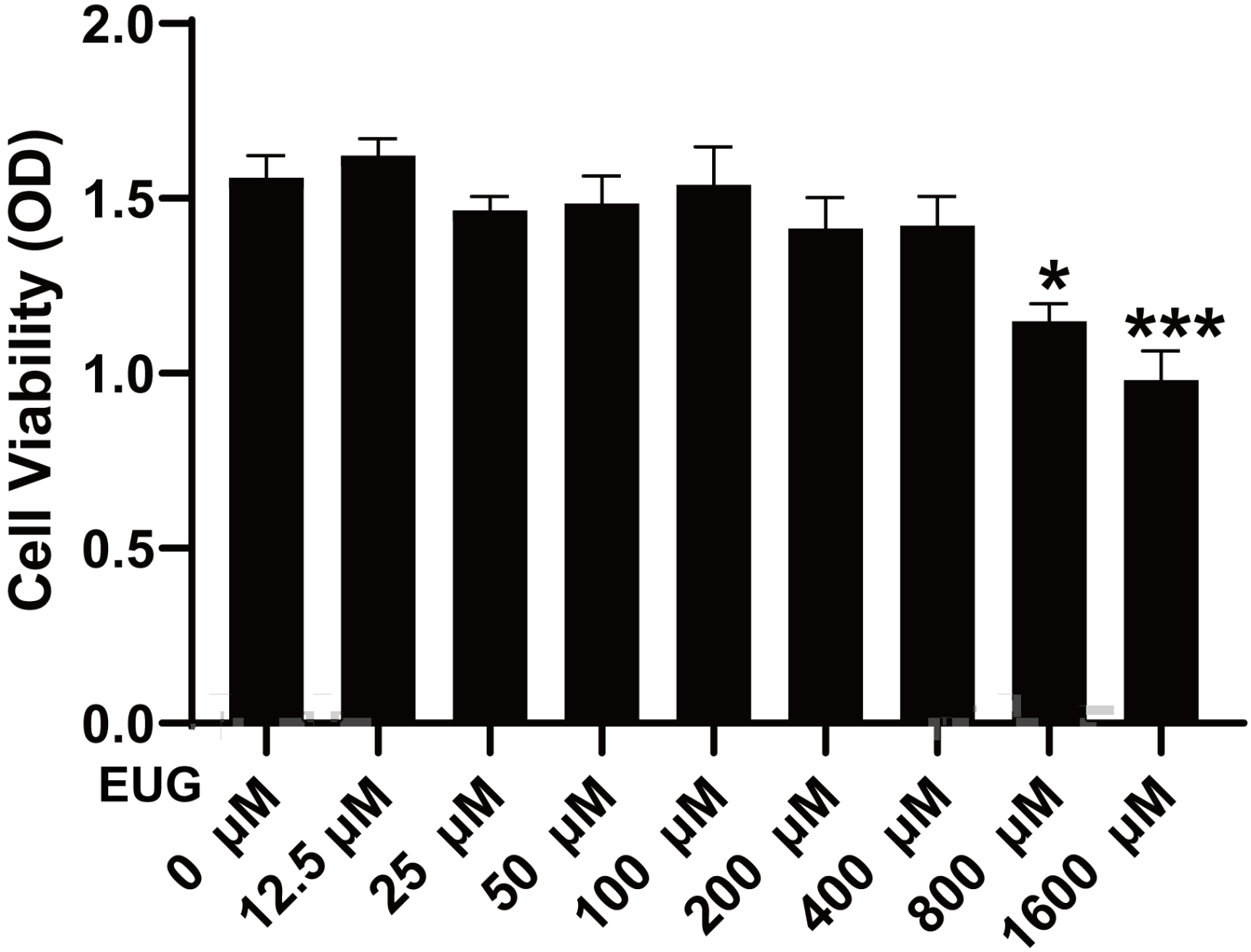
Figure 6-Source Data 1. Western blot raw image.

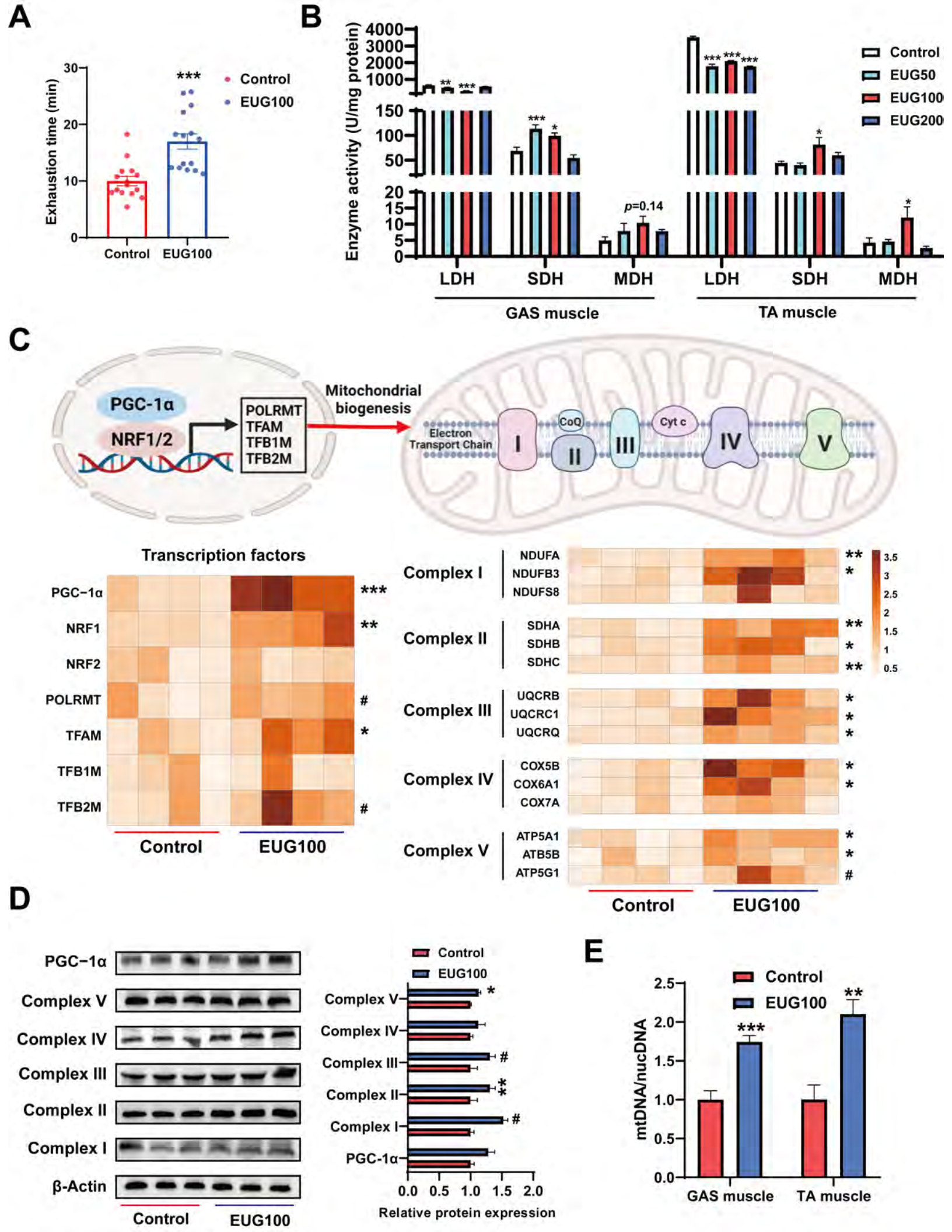
Figure 7-Source Data 1. Western blot raw image.

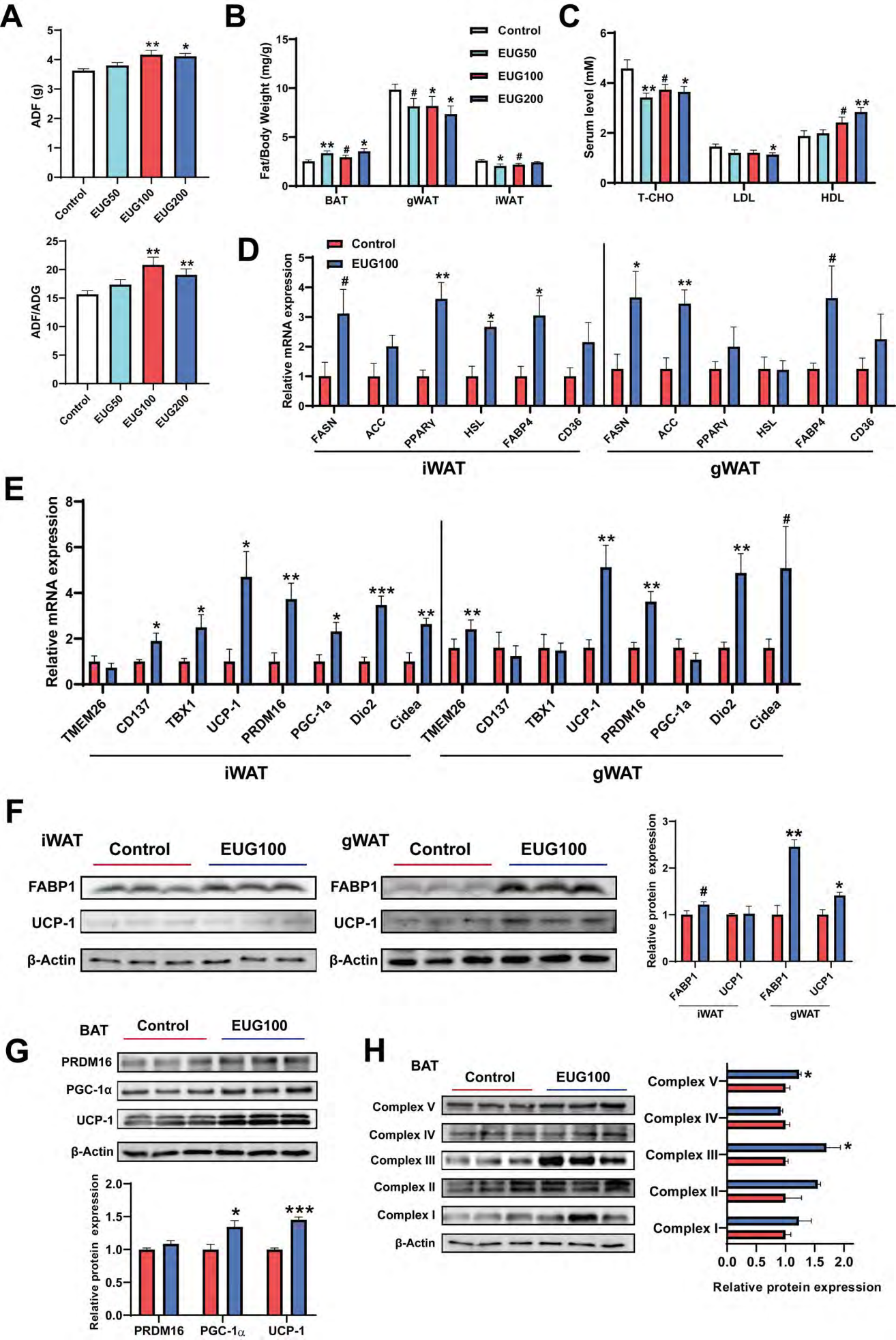
Figure 8-Source Data 1. Western blot raw image.

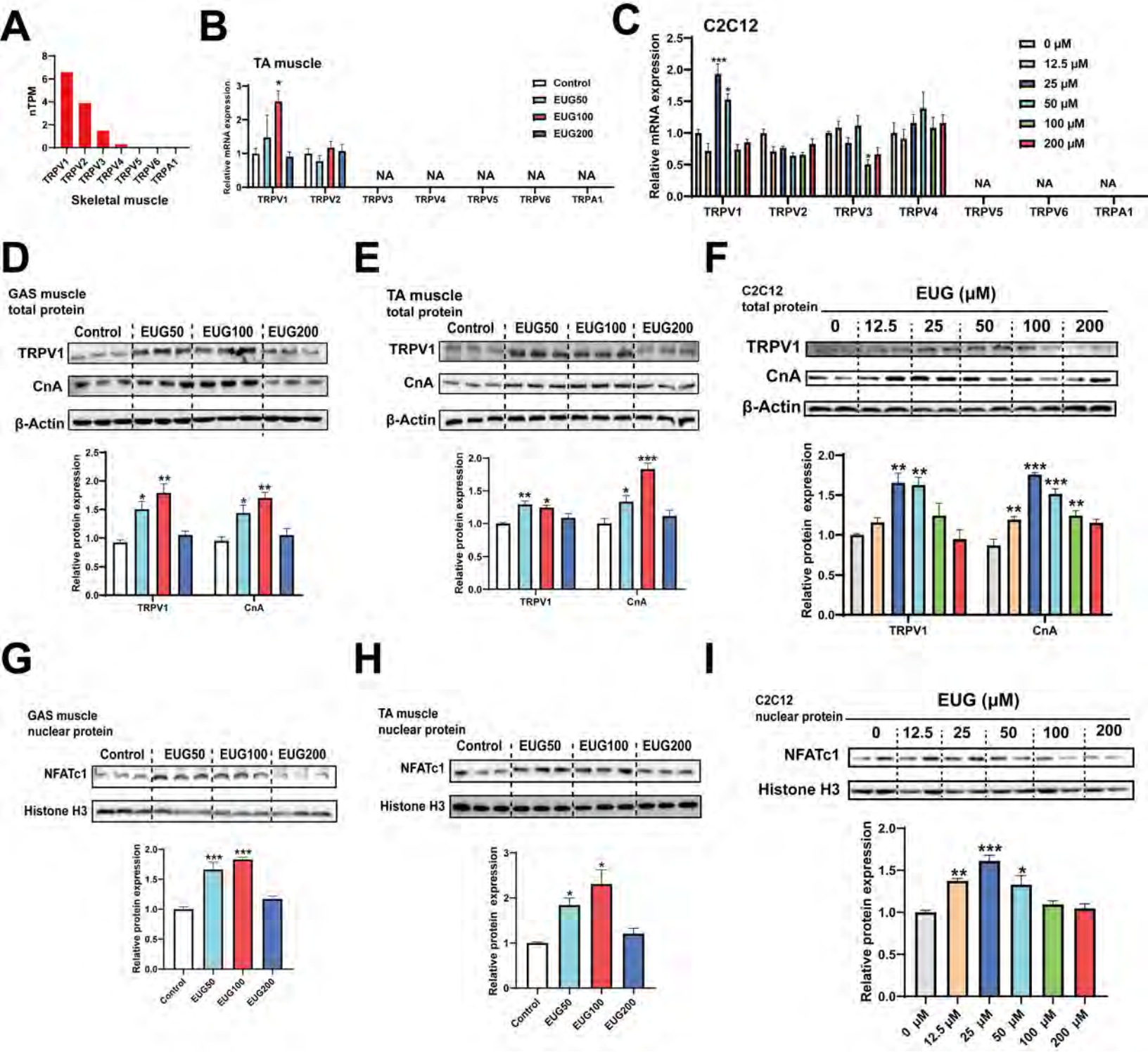
Figure 9-Source Data 1. Western blot raw image.

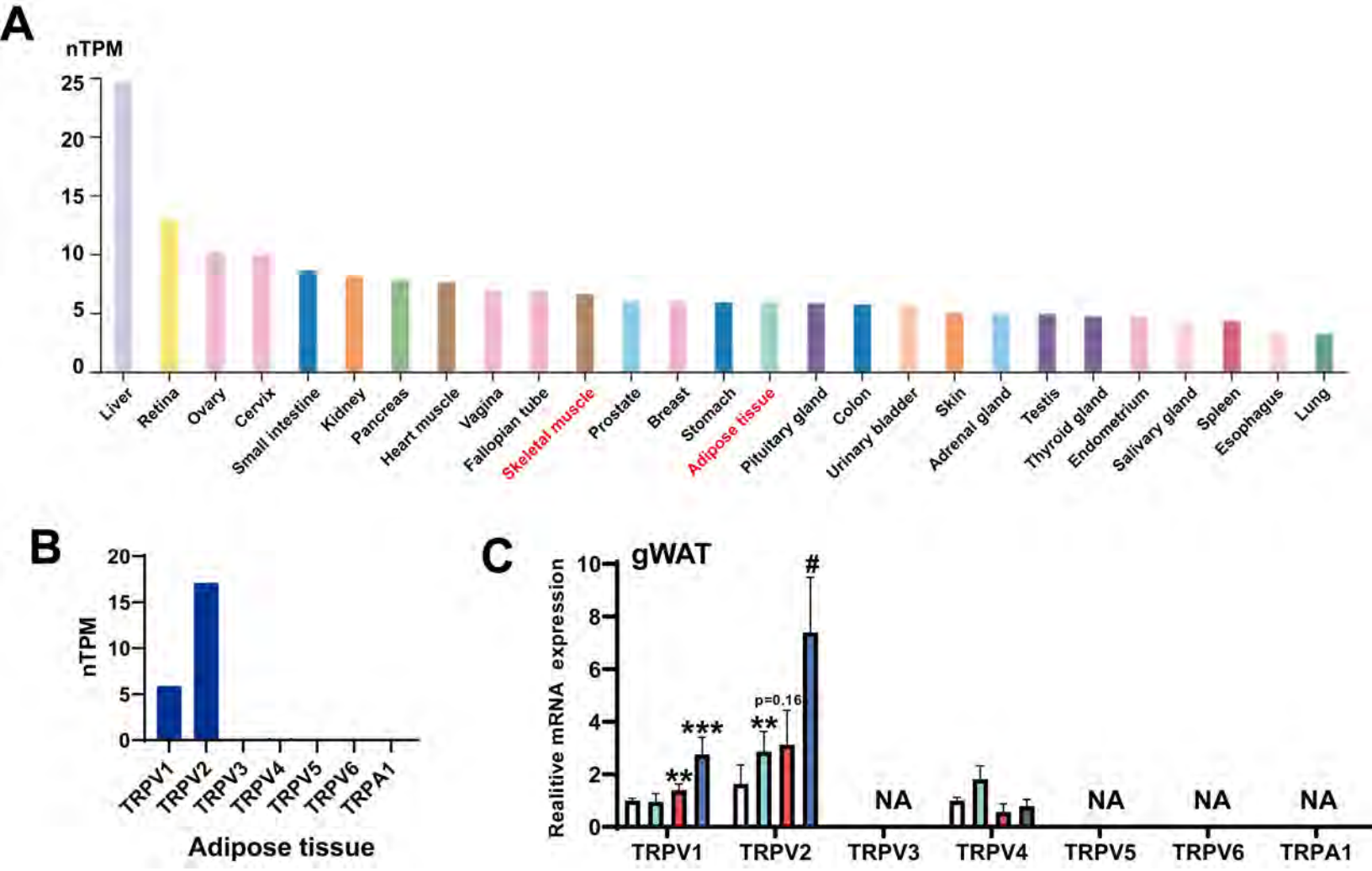

A
Control
EUG50
EUG100
EUG200
Body weight (g)
Weeks of treatment
B
Control
EUG50
EUG100
EUG200
Muscle/Body Weight (mg/g)
TA
EDL
SOL
GAS
C
TA
EDL
SOL
GAS
Control
EUG50
EUG100
EUG200
D
GAS muscle
Control
EUG50
EUG100
EUG200
Slow MyHC
Fast MyHC
β-Actin
Relative protein expression
Slow MyHC
Fast MyHC
E
TA muscle
Control
EUG50
EUG100
EUG200
Slow MyHC
Fast MyHC
β-Actin
Relative protein expression
Slow MyHC
Fast MyHC
F
EUG (μM)
C2C12
0
12.5
25
50
100
200
Slow MyHC
Fast MyHC
β-Actin
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM
Relative protein expression
Slow MyHC
Fast MyHC
G
Sketeal muscle
Relative mRNA expression
MyHC I
MyHC IIa
MyHC IIx
MyHC IIb
MyHC I
MyHC IIa
MyHC IIx
MyHC IIb
GAS muscle
TA muscle
H
C2C12
Relative mRNA expression
MyHC I
MyHC IIa
MyHC IIx
MyHC IIb

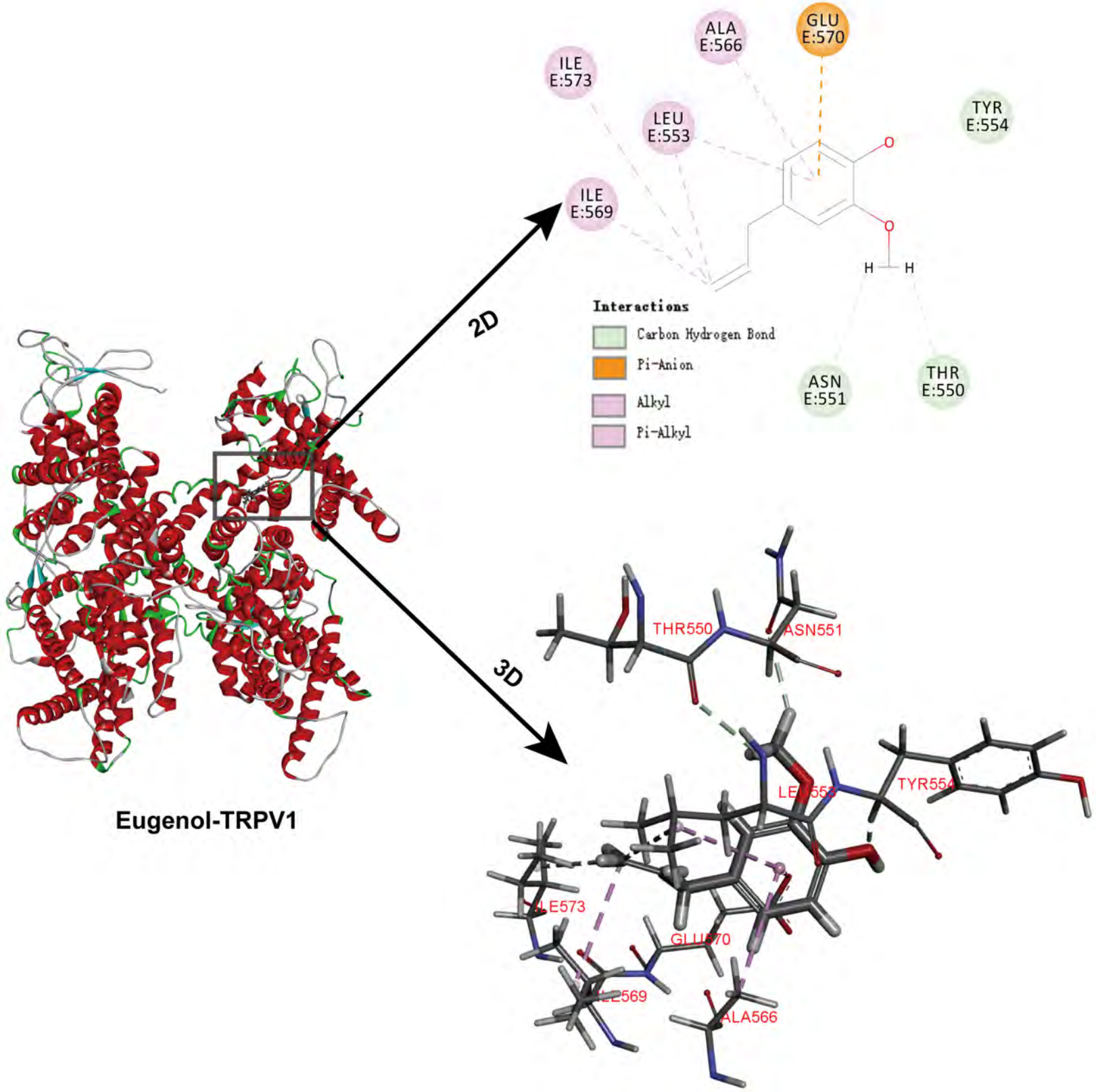

Cell Viability (OD)
2.0
1.5
1.0
0.5
0.0
*
***
EUG
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM
400 μM
800 μM
1600 μM

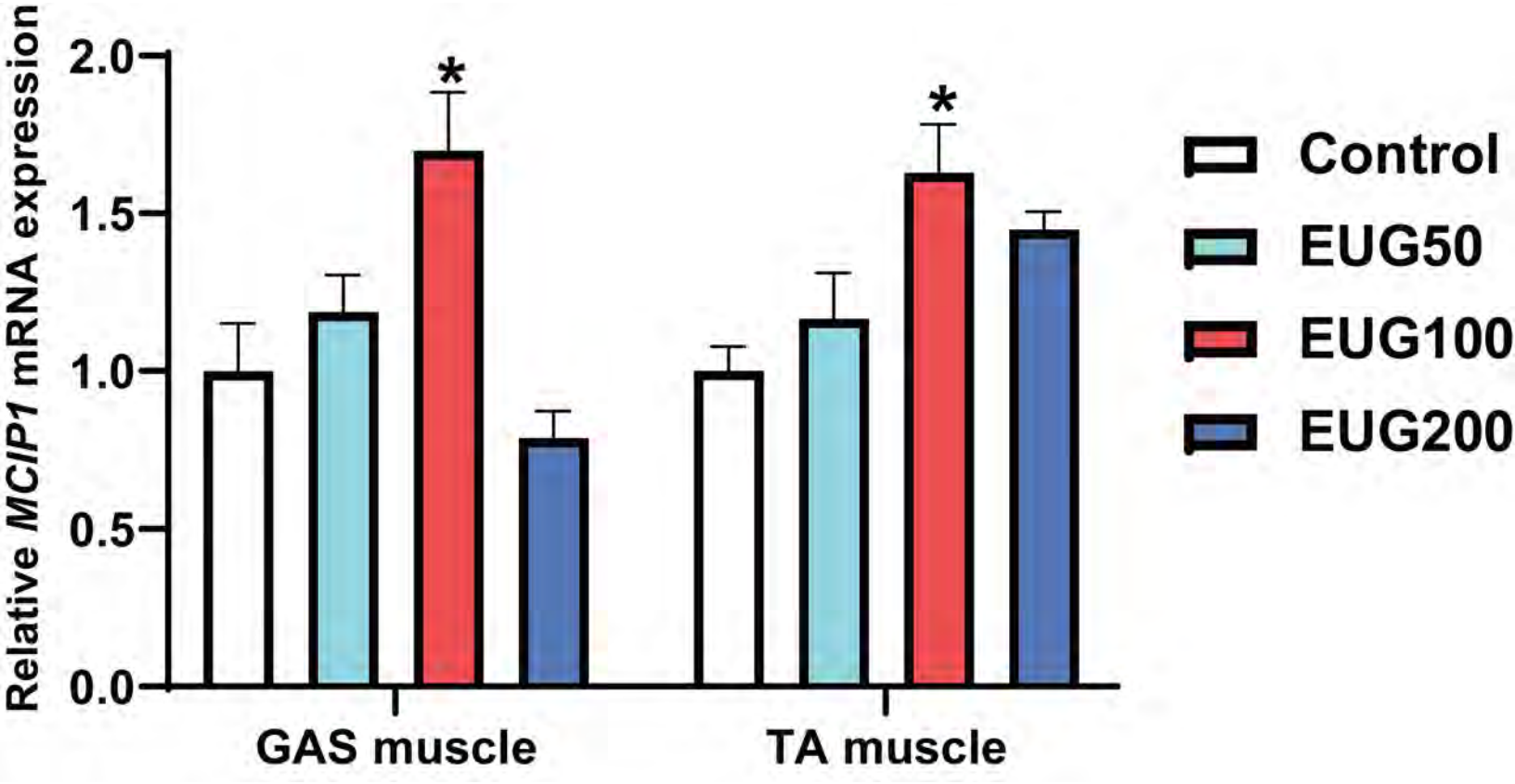

A
Exhaustion time (min)
Control
EUG100
B
Enzyme activity (U/mg protein)
Control
EUG50
EUG100
EUG200
p=0.14
LDH
SDH
MDH
GAS muscle
TA muscle
C
PGC-1α
NRF1/2
POLRMT
TFAM
TFB1M
TFB2M
Mitochondrial biogenesis
Electron Transport Chain
CoQ
Cyt c
Transcription factors
Complex I
Complex II
Complex III
Complex IV
Complex V
NDUFA
NDUFB3
NDUFS8
SDHA
SDHB
SDHC
UQCRB
UQCRC1
UQCRQ
COX5B
COX6A1
COX7A
ATP5A1
ATB5B
ATP5G1
D
β-Actin
Relative protein expression
E
mtDNA/nucDNA

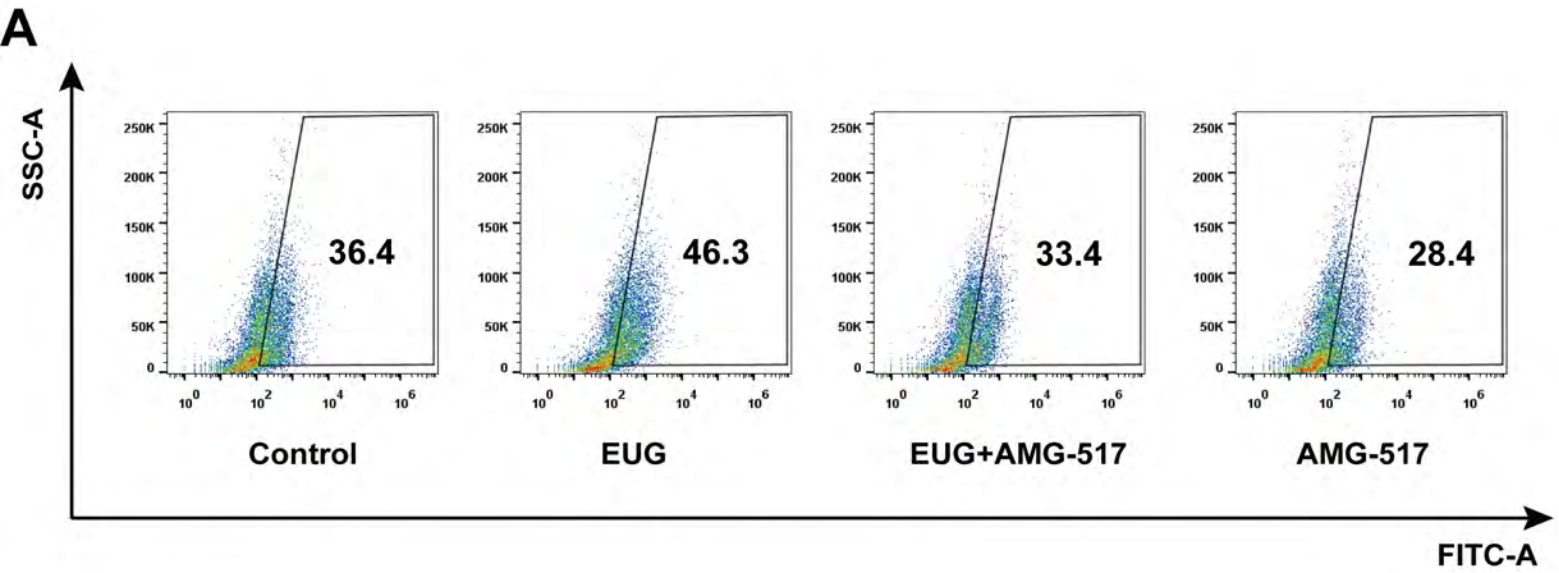

A
ADF (g)
Control
EUG50
EUG100
EUG200
ADF/ADG
B
Fat/Body Weight (mg/g)
BAT
gWAT
iWAT
C
Serum level (mM)
T-CHO
LDL
HDL
D
Relative mRNA expression
FASN
ACC
PPARγ
HSL
FABP4
CD36
iWAT
gWAT
E
Relative mRNA expression
TMEM26
CD137
TBX1
UCP-1
PRDM16
PGC-1a
Dio2
Cidea
iWAT
gWAT
F
iWAT
Control
EUG100
FABP1
UCP-1
β-Actin
gWAT
Relative protein expression
G
BAT
PRDM16
PGC-1α
UCP-1
β-Actin
H
Complex V
Complex IV
Complex III
Complex II
Complex I
β-Actin
Relative protein expression

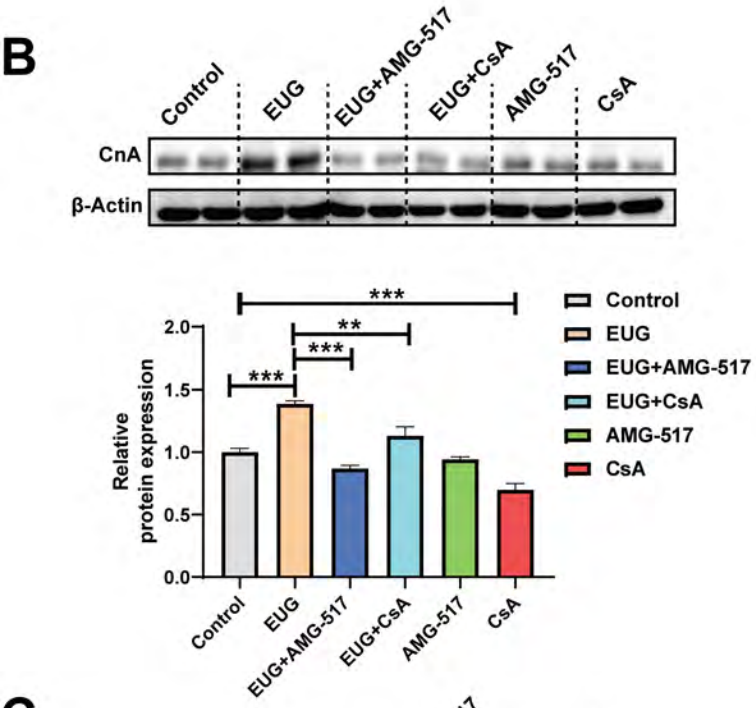

A
nTPM
TRPV1
TRPV2
TRPV3
TRPV4
TRPV5
TRPV6
TRPA1
Skeletal muscle
B
TA muscle
Relative mRNA expression
Control
EUG50
EUG100
EUG200
NA
C
C2C12
Relative mRNA expression
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM
D
GAS muscle
total protein
Control
EUG50
EUG100
EUG200
TRPV1
CnA
β-Actin
Relative protein expression
E
TA muscle
total protein
F
C2C12
total protein
EUG (μM)
0
12.5
25
50
100
200
G
GAS muscle
nuclear protein
NFATc1
Histone H3
H
TA muscle
nuclear protein
I
C2C12
nuclear protein
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM

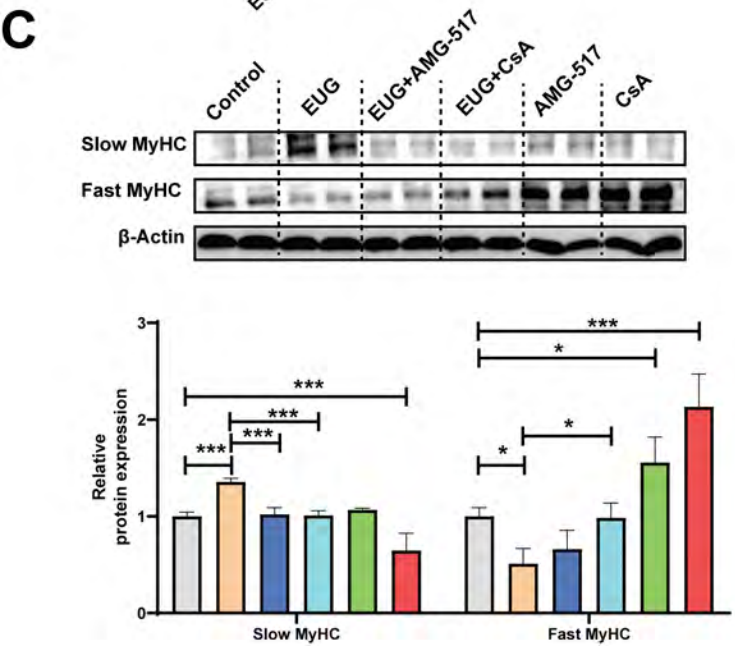

A
nTPM
25
20
15
10
5
0
Liver
Retina
Ovary
Cervix
Small intestine
Kidney
Pancreas
Heart muscle
Vagina
Fallopian tube
Skeletal muscle
Prostate
Breast
Stomach
Adipose tissue
Pituitary gland
Colon
Urinary bladder
Skin
Adrenal gland
Testis
Thyroid gland
Endometrium
Salivary gland
Spleen
Esophagus
Lung
B
nTPM
20
15
10
5
0
TRPV1
TRPV2
TRPV3
TRPV4
TRPV5
TRPV6
TRPA1
Adipose tissue
C
gWAT
Realitive mRNA expression
10
8
6
4
2
0
**
***
**
p=0.16
#
NA
NA
NA
NA
TRPV1
TRPV2
TRPV3
TRPV4
TRPV5
TRPV6
TRPA1

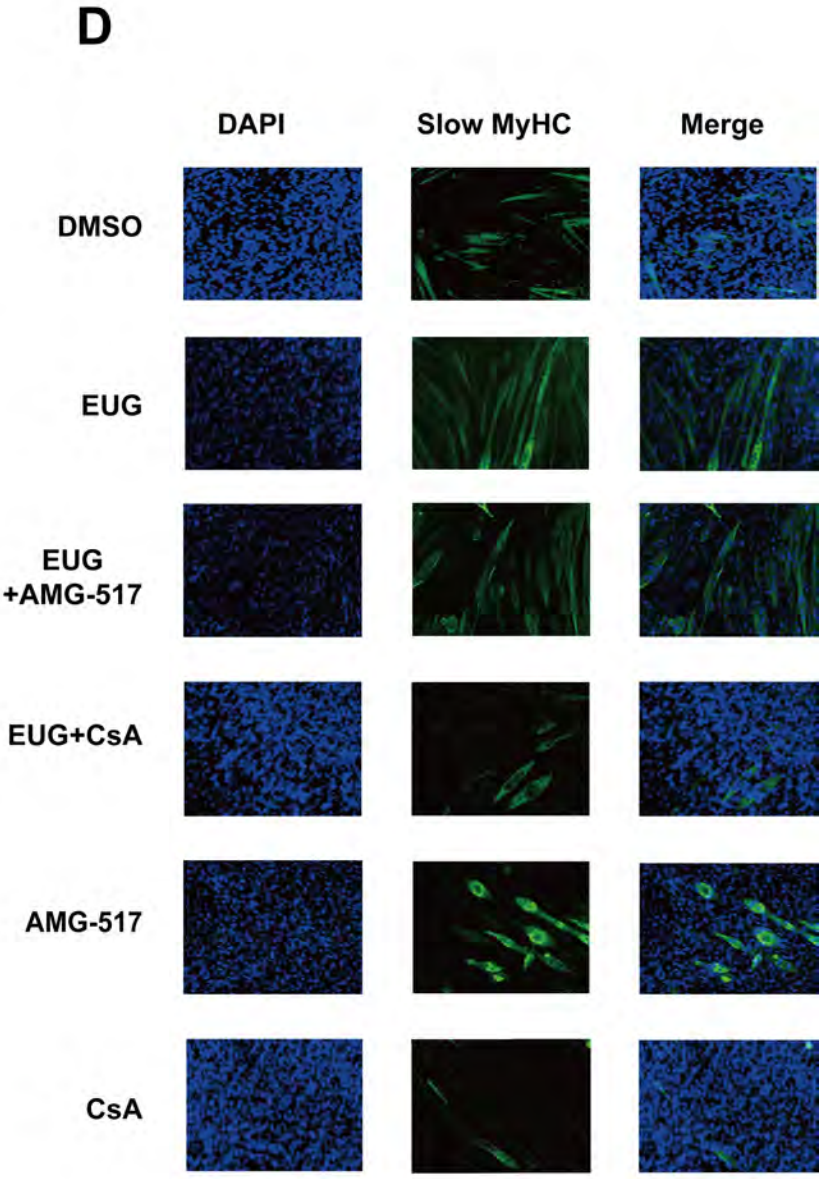

ILE E:573
ALA E:566
GLU E:570
LEU E:553
TYR E:554
ILE E:569
O
O
H
H
Interactions
Carbon Hydrogen Bond
Pi-Anion
Alkyl
Pi-Alkyl
ASN E:551
THR E:550
2D
3D
Eugenol-TRPV1
THR550
ASN551
LEU553
TYR554
ILE573
GLU570
ILE569
ALA566

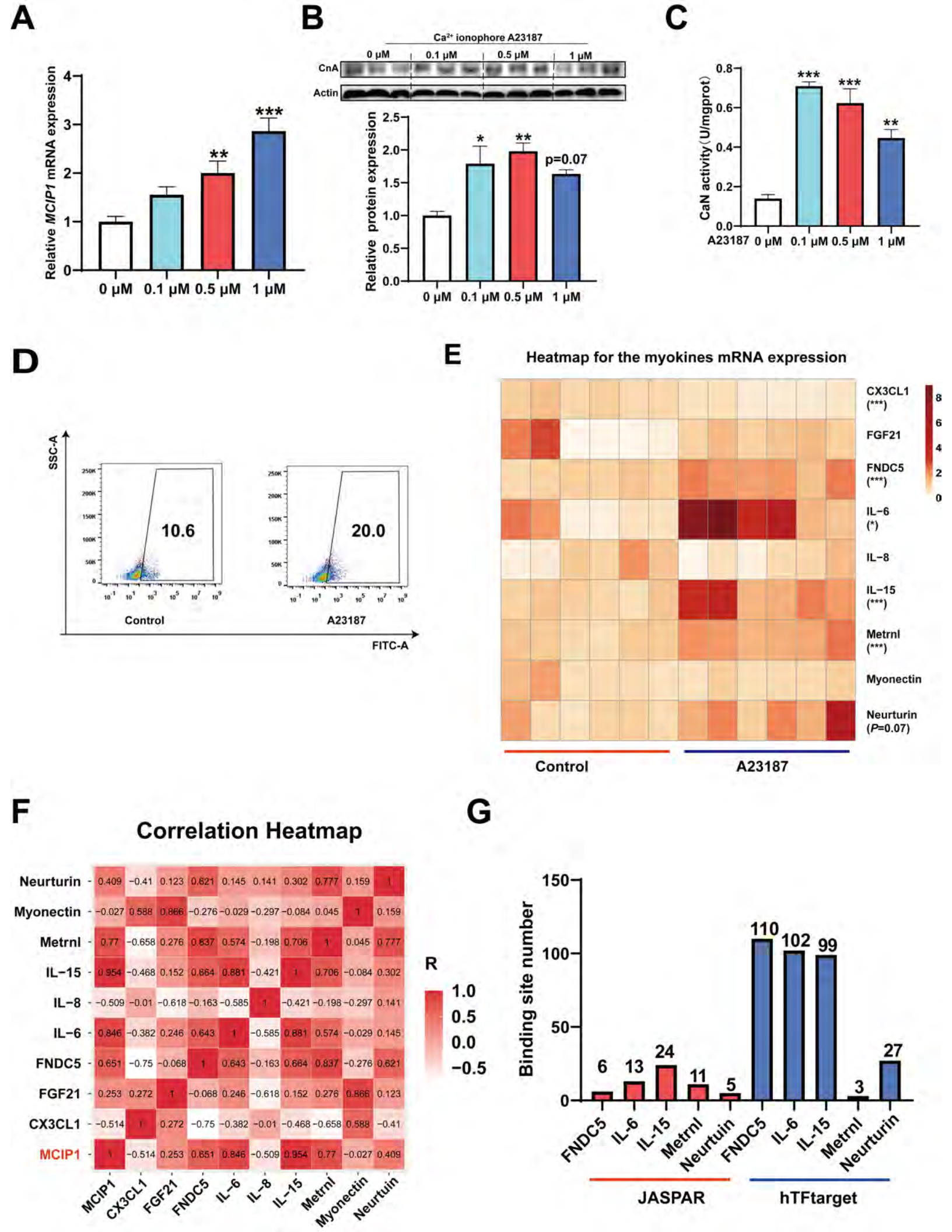

Relative MCIP1 mRNA expression
2.0
1.5
1.0
0.5
0.0
*
*
GAS muscle
TA muscle
Control
EUG50
EUG100
EUG200

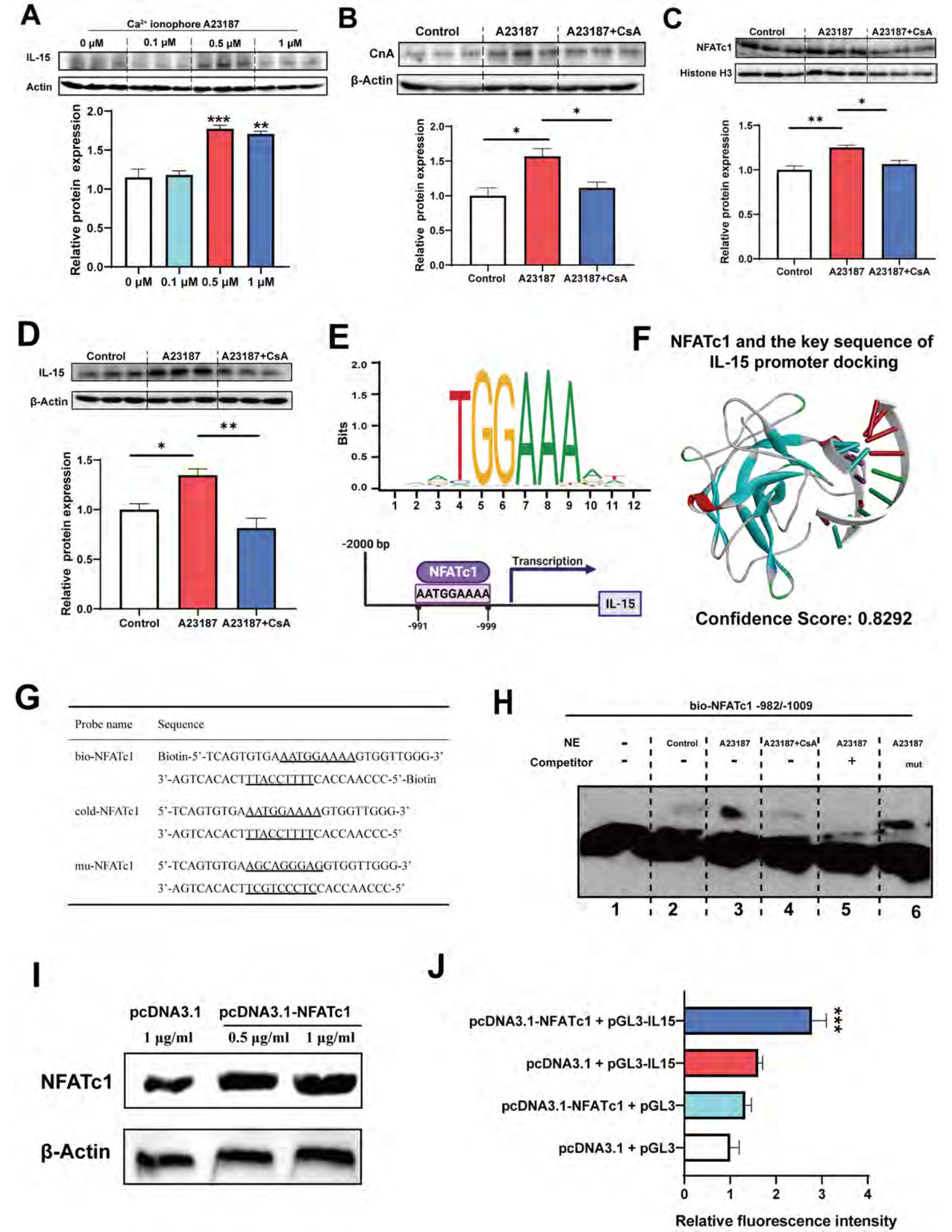

A
SSC-A
FITC-A
36.4
46.3
33.4
28.4
Control
EUG
EUG+AMG-517
AMG-517

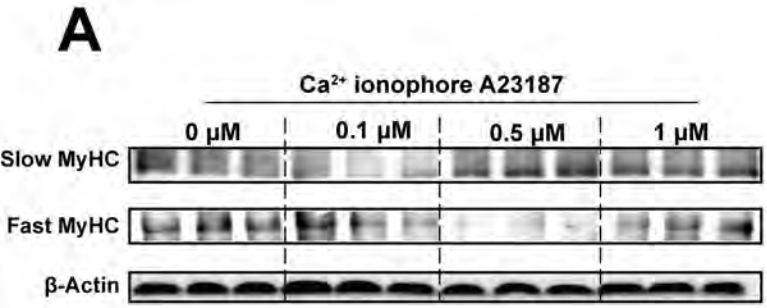

B
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA
CnA
β-Actin
Relative protein expression
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA

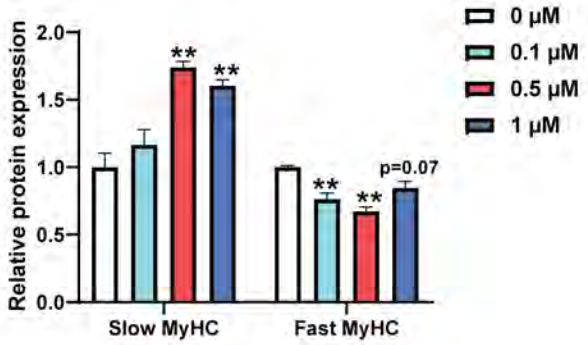

C
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA
Slow MyHC
Fast MyHC
β-Actin
Relative protein expression
Slow MyHC
Fast MyHC

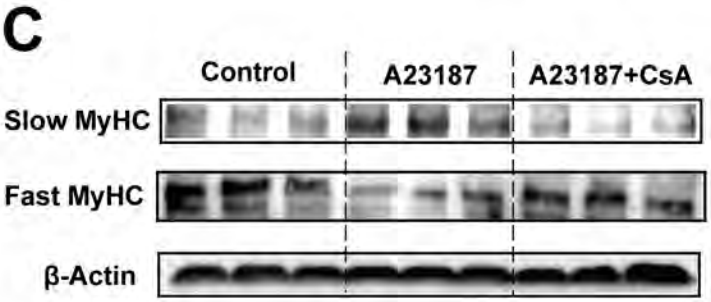

D
DAPI
Slow MyHC
Merge
DMSO
EUG
EUG +AMG-517
EUG+CsA
AMG-517
CsA

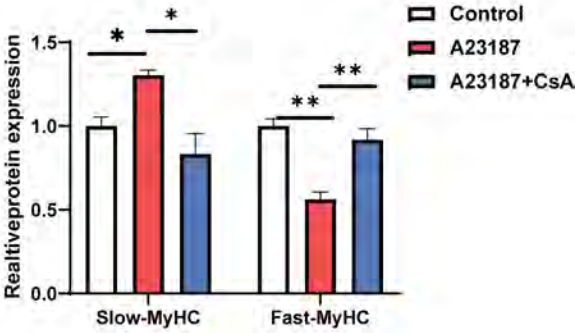

A
Relative MCIP1 mRNA expression
0 μM
0.1 μM
0.5 μM
1 μM
B
Ca²⁺ ionophore A23187
CnA
Actin
Relative protein expression
p=0.07
C
CaN activity（U/mgprot）
A23187
D
SSC-A
FITC-A
Control
A23187
10.6
20.0
E
Heatmap for the myokines mRNA expression
CX3CL1 (***)
FGF21
FNDC5 (***)
IL−6 (*)
IL−8
IL−15 (***)
Metrnl (***)
Myonectin
Neurturin (P=0.07)
Control
A23187
F
Correlation Heatmap
Neurturin
Myonectin
Metrnl
IL−15
IL−8
IL−6
FNDC5
FGF21
CX3CL1
MCIP1
R
G
Binding site number
FNDC5
IL-6
IL-15
Metrnl
Neurtuin
JASPAR
hTFtarget

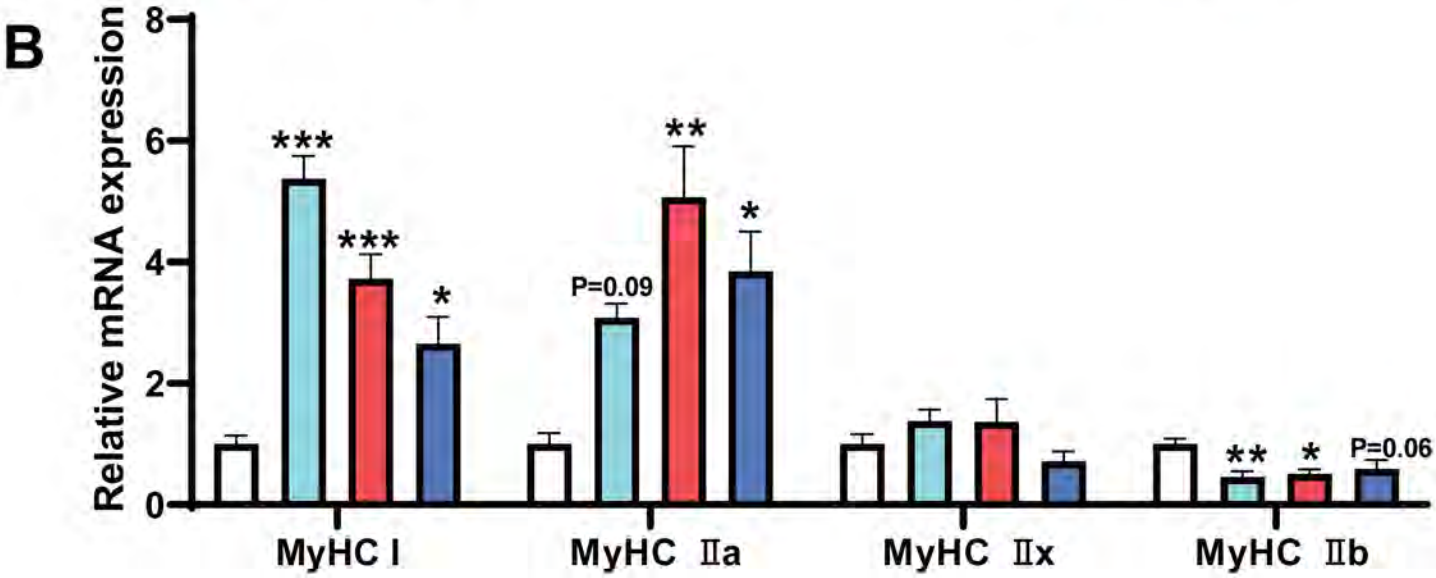

A
Ca2+ ionophore A23187
0 μM
0.1 μM
0.5 μM
1 μM
IL-15
Actin
Relative protein expression
B
Control
A23187
A23187+CsA
CnA
β-Actin
C
NFATc1
Histone H3
D
IL-15
β-Actin
E
Bits
-2000 bp
NFATc1
AATGGAAAA
Transcription
IL-15
-991
-999
F
NFATc1 and the key sequence of IL-15 promoter docking
Confidence Score: 0.8292
G
Probe name
Sequence
bio-NFATc1
Biotin-5'-TCAGTGTGAAATGGAAAAGTGGTTGGG-3'
3'-AGTCACACTTTACCTTTTCACCAACCC-5'-Biotin
cold-NFATc1
5'-TCAGTGTGAAATGGAAAAGTGGTTGGG-3'
3'-AGTCACACTTTACCTTTTCACCAACCC-5'
mu-NFATc1
5'-TCAGTGTGAAGCAGGGAGGTGGTTGGG-3'
3'-AGTCACACTTCGTCCCTCCACCAACCC-5'
H
bio-NFATc1 -982/-1009
NE
Competitor
mut
I
pcDNA3.1
pcDNA3.1-NFATc1
1 μg/ml
0.5 μg/ml
1 μg/ml
NFATc1
β-Actin
J
pcDNA3.1-NFATc1 + pGL3-IL15
pcDNA3.1 + pGL3-IL15
pcDNA3.1-NFATc1 + pGL3
pcDNA3.1 + pGL3
Relative fluorescence intensity

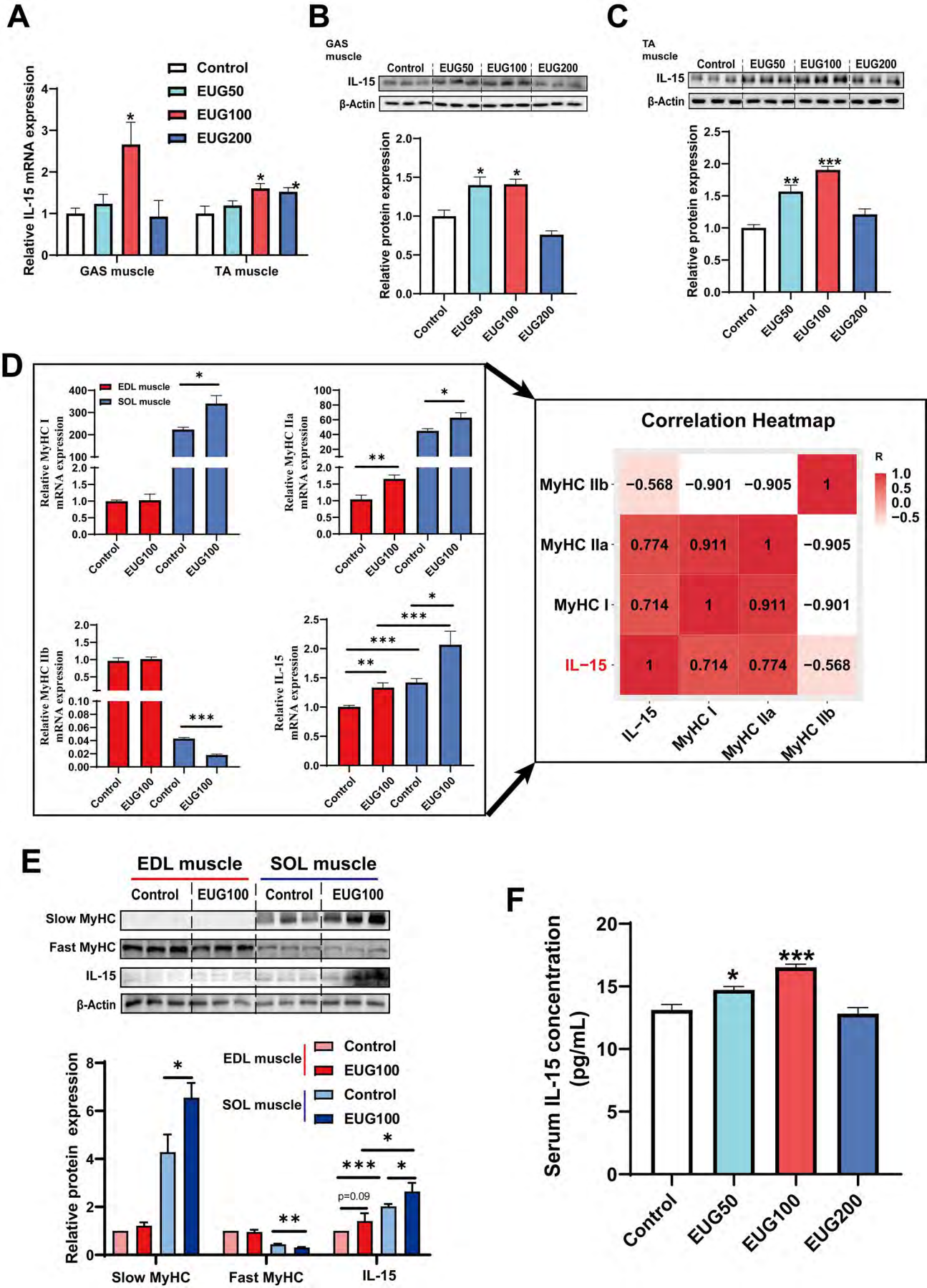

A
Ca²⁺ ionophore A23187
0 μM
0.1 μM
0.5 μM
1 μM
Slow MyHC
Fast MyHC
β-Actin

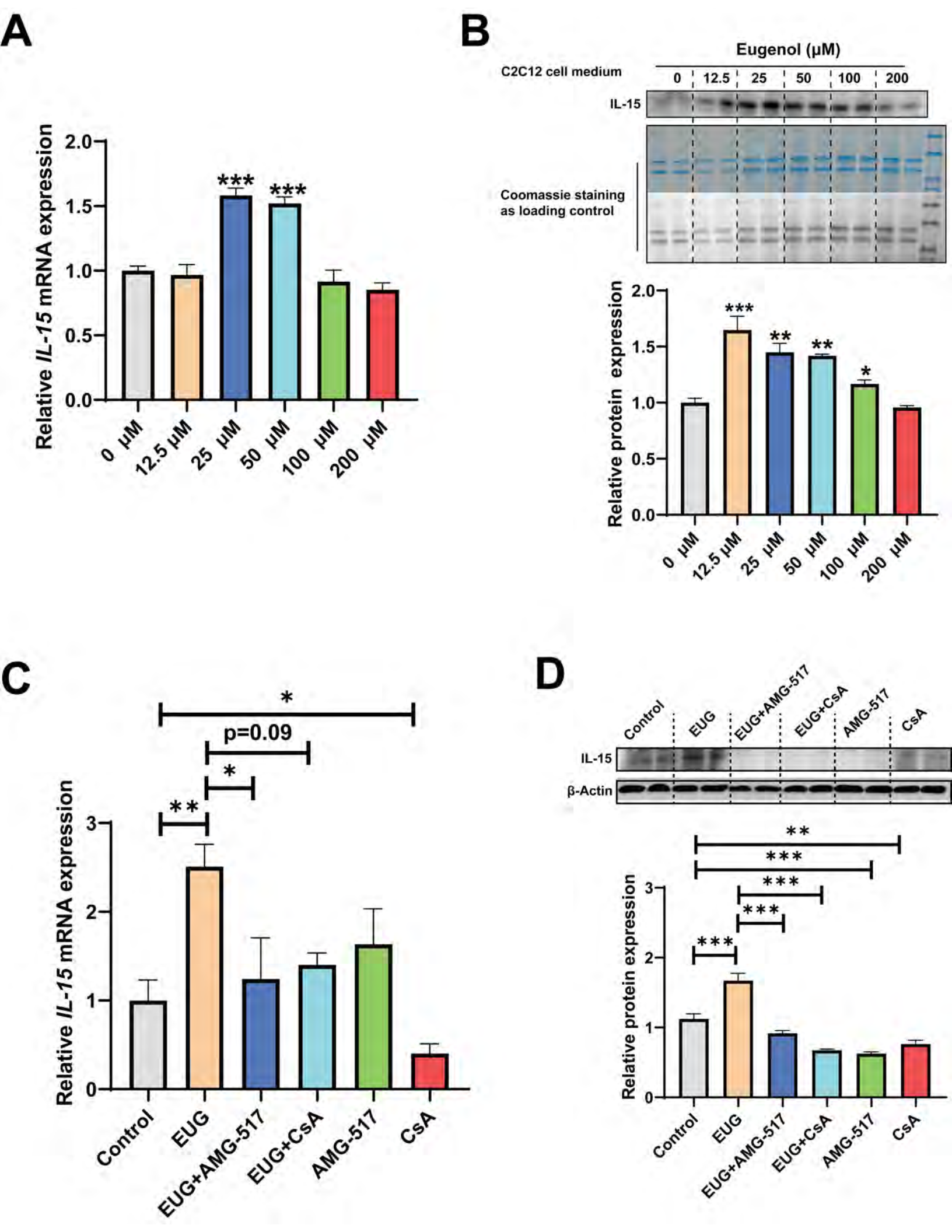

Relative protein expression
2.0
1.5
1.0
0.5
0.0
**
**
**
**
p=0.07
Slow MyHC
Fast MyHC
0 μM
0.1 μM
0.5 μM
1 μM

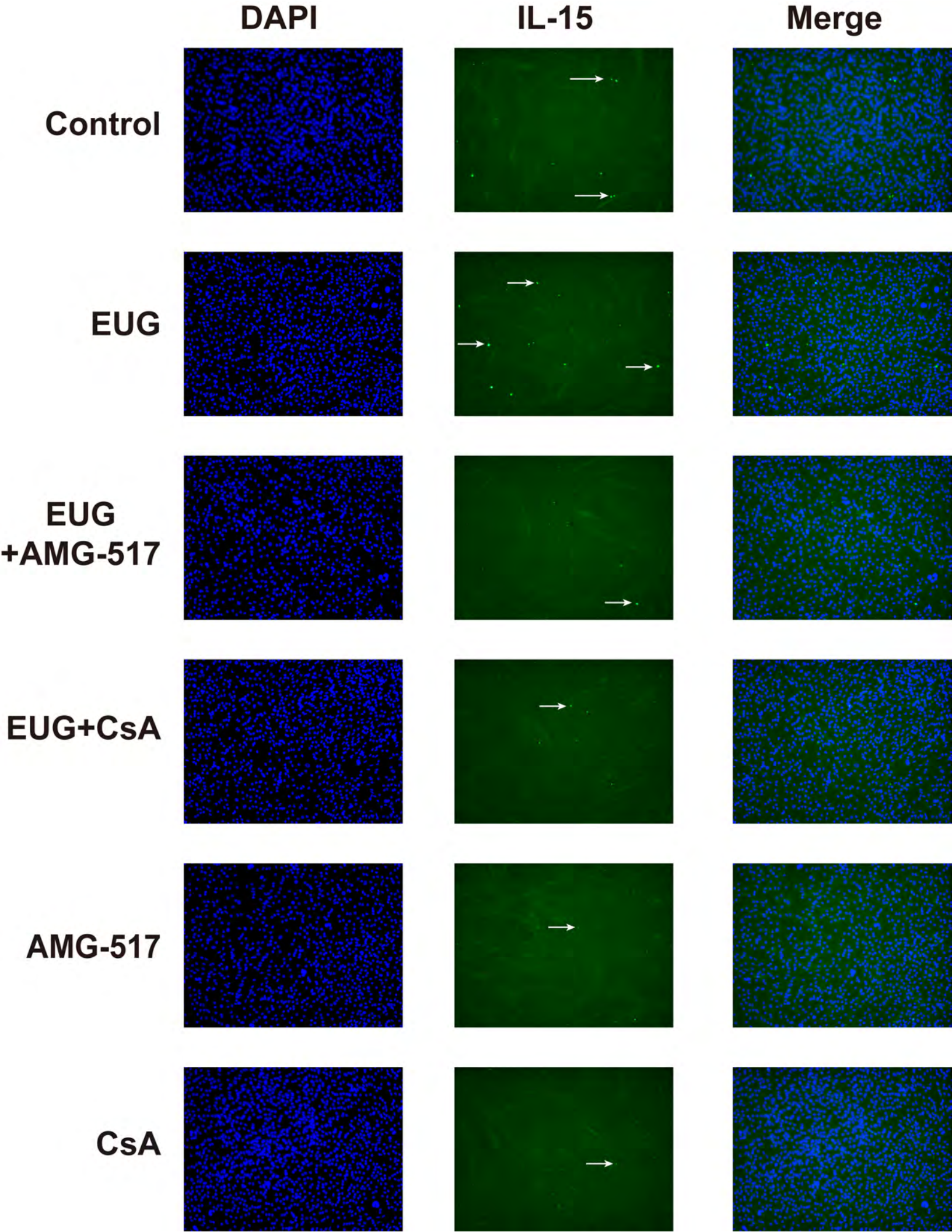

C
Control
A23187
A23187+CsA
Slow MyHC
Fast MyHC
β-Actin


Realtiveprotein expression
1.5
1.0
0.5
0.0
*
*
**
**
Slow-MyHC
Fast-MyHC
Control
A23187
A23187+CsA


B
Relative mRNA expression
8
6
4
2
0
***
***
*
P=0.09
**
*
**
*
P=0.06
MyHC Ⅰ
MyHC Ⅱa
MyHC Ⅱx
MyHC Ⅱb


A
Control
EUG50
EUG100
EUG200
Relative IL-15 mRNA expression
GAS muscle
TA muscle
B
GAS muscle
Control
EUG50
EUG100
EUG200
IL-15
β-Actin
Relative protein expression
C
TA muscle
D
EDL muscle
SOL muscle
Relative MyHC I mRNA expression
Relative MyHC IIa mRNA expression
Relative MyHC IIb mRNA expression
Relative IL-15 mRNA expression
Correlation Heatmap
R
MyHC IIb
MyHC IIa
MyHC I
IL-15
E
EDL muscle
SOL muscle
Slow MyHC
Fast MyHC
IL-15
β-Actin
Relative protein expression
p=0.09
F
Serum IL-15 concentration (pg/mL)


A
Relative IL-15 mRNA expression
2.0
1.5
1.0
0.5
0.0
***
***
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM
B
Eugenol (μM)
C2C12 cell medium
0
12.5
25
50
100
200
IL-15
Coomassie staining as loading control
Relative protein expression
2.0
1.5
1.0
0.5
0.0
***
**
**
*
0 μM
12.5 μM
25 μM
50 μM
100 μM
200 μM
C
*
p=0.09
*
**
Relative IL-15 mRNA expression
3
2
1
0
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA
D
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA
IL-15
β-Actin
**
***
***
***
***
Relative protein expression
3
2
1
0
Control
EUG
EUG+AMG-517
EUG+CsA
AMG-517
CsA


DAPI
IL-15
Merge
Control
EUG
EUG
+AMG-517
EUG+CsA
AMG-517
CsA