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Identification of a Sesquiterpene Lactone from *Arctium lappa* Leaves with Antioxidant Activity in Primary Human Muscle Cells

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Abstract: Many pathologies affecting muscles (muscular dystrophies, sarcopenia, cachexia, renal insufficiency, obesity, diabetes type 2, etc.) are now clearly linked to mechanisms involving oxidative stress. In this context, there is a growing interest in exploring plants to find new natural antioxidants to prevent the appearance and the development of these muscle disorders. In this study, we investigated the antioxidant properties of *Arctium lappa* leaves in a model of primary human muscle cells exposed to H₂O₂ oxidative stress. We identified using bioassay-guided purification, onopordopicrin, a sesquiterpene lactone as the main molecule responsible for the antioxidant activity of *A. lappa* leaf extract. According to our findings, onopordopicrin inhibited the H₂O₂-mediated loss of muscle cell viability, by limiting the production of free radicals and abolishing DNA cellular damages. Moreover, we showed that onopordopicrin promoted the expression of the nuclear factor-erythroid-2-related factor 2 (Nrf2) downstream target protein heme oxygenase-1 (HO-1) in muscle cells. By using siRNA, we demonstrated that the inhibition of the expression of Nrf2 reduced the protective effect of onopordopicrin, indicating that the activation of the Nrf2/HO-1 signaling pathway mediates the antioxidant effect of onopordopicrin in primary human muscle cells. Therefore, our results suggest that onopordopicrin may be a potential therapeutic molecule to fight against oxidative stress in pathological specific muscle disorders.

Keywords: *Arctium lappa* L.; burdock leaves; antioxidant; onopordopicrin; human myoblasts

1. Introduction

Oxidative stress, defined as an imbalance between pro-oxidants (reactive oxygen species—ROS) and antioxidants in favor of pro-oxidants is now proposed to be a common denominator in the pathogenesis of most chronic diseases such as cancer, coronary heart disease, neurodegenerative diseases, obesity, diabetes type 2, hypertension [1]. ROS, that are by-products of oxidative phosphorylation, would cause progressive damage to key cell macromolecules (lipids, proteins, and DNA), altering both their structure and function. In muscle-specific disorders such as muscular dystrophies and during aging, oxidative stress is proposed to be a major causal factor of muscle wasting [2–6]. The process of protein synthesis and degradation that controls muscle mass has been shown to be redox-sensitive [5]. Elevated oxidative stress can result in irreversible cellular damage. It has been associated with telomere shortening, the alteration of muscle cell proliferation, differentiation and muscle stem cell depletion during aging in a mice model of muscle degenerative disease [7–10]. Many mechanisms have been proposed to explain muscle degeneration caused by the accumulation of ROS. Among these, the loss of calcium homeostasis as a result of alteration of the ion channel membrane proteins, mitochondrial

dysfunction, the activation of NF- κ B which results in the expression of inflammatory genes, autophagy, a mechanism that allows the removal of defective proteins and organelles [6].

Despite the clinical relevance of antioxidant use as a therapeutic approach to improve muscle function and the great interest of a broad segment of the population in antioxidant supplementation, evidence in this field is very limited and the effect of antioxidants in delaying, preventing, or reversing the loss of muscle mass is unclear [11]. The difficulty is that the choice of antioxidant molecules is often based on their availability and not on their effectiveness. Generally, clinical trials are not preceded by pre-tests evaluating the effectiveness and toxicity of antioxidant molecules, tests that would allow selection of those that are most effective and the least toxic. In terms of toxicity, some antioxidants have been shown to have deleterious effects on the differentiation of cell precursors of skeletal, cardiac, smooth muscle and adipose tissues [12–17].

Arctium lappa L. (Asteraceae), commonly called burdock, is a popular plant in folk medicine widely used in China and other parts of the world. *Arctium lappa* (*A. lappa*) has recognized healthy effects and is applied to treat various diseases including diabetes, gout, rheumatism and skin problems [18–21]. Research on *A. lappa* extracts obtained from roots, seeds and leaves has identified several classes of bioactive secondary metabolites including lignans, flavonoids, quinic acids, phenolics, polyacetylenes, terpenoids, lactones and polysaccharides [22]. Many of the biological properties attributed to *A. lappa*, including antimutagenicity, anticancer, and antiaging, may originate from the ability of its components to reduce inflammation and oxidative stress [23–25]. As *A. lappa* leaves are poorly characterized compared to the other parts of the plants (roots, seeds and fruits) and few data are reported in literature, we decided to focus our research on leaf extracts of *A. lappa*. This choice was also supported by the fact that *A. lappa* leaves, being discarded following roots and seeds harvesting, become a plant waste material available for the valorization of bioactive compounds. In a previous study on *A. lappa* leaves, Franco et al. [26] showed that ethanol extracts present high antioxidant capacities in in vitro assays such as the scavenging of free radicals (DPPH assay) and oxygen radical absorbance capacity (ORAC assay). Another work also using the DPPH assay pointed out the hydroalcoholic extracts of *A. lappa* leaves as antioxidant [27]. In this study, Lou and collaborators showed that the antioxidant capacity was associated with the total phenolic content of extracts. Moreover, they suggested that compounds such as chlorogenic acid, o-hydroxybenzoic acid, caffeic acid, *p*-coumaric acid and rutin present in *A. lappa* leaves extracts could be involved in antioxidant activity. More recently, Kim et al. [28] showed that an *A. lappa* leaves extract has a protective effect on an age-related macular degeneration model and they suggested that this effect could be due to antioxidant properties of phenolic and flavonoid content present in the leaves extract. Thus, all these studies have reported a potential antioxidant ability of *A. lappa* leaves but no specific compound has been isolated from the extracts.

In this study, we first developed a cellular assay for testing antioxidant activities of *A. lappa* leaves in a model of stressed-human skeletal muscle cells with hydrogen peroxide (H₂O₂), a strong pro-oxidant molecule. Then, we used a bioassay-guided fractionation to identify bioactive molecules from leaves of *A. lappa*. Finally, we studied the capacity of the identified antioxidant molecule to protect primary human muscle cells from oxidative stress, by measuring cell viability, levels of ROS, and DNA damage as well as the activation of the Nrf2 signaling pathway.

2. Results

2.1. Antioxidant Activity of *Arctium lappa* Leaf Extract and Bioactivity-Guided Separation of Antioxidant Compounds

We previously showed that the pro-oxidant molecule H₂O₂ increases the percentage of apoptotic cells in adherent cultures of primary human myoblasts (skeletal muscle precursor cells) [29]. We used this model of H₂O₂-treated human skeletal muscle cells to screen the antioxidant activity of an ethanolic *A. lappa* leaves extract (burdock leaves extract, BL). We pre-incubated human myoblasts with increasing concentrations of BL extract prior to the addition of a lethal concentration of H₂O₂ in the culture medium. BL pre-incubated at 70

and 140 $\mu\text{g}/\text{mL}$ for 24 h with myoblasts drastically reducing cell death (Figure 1A). We determined that both these concentrations of BL were also able to efficiently decrease the levels of ROS produced by the cells following the addition of H_2O_2 (Figure 1B).

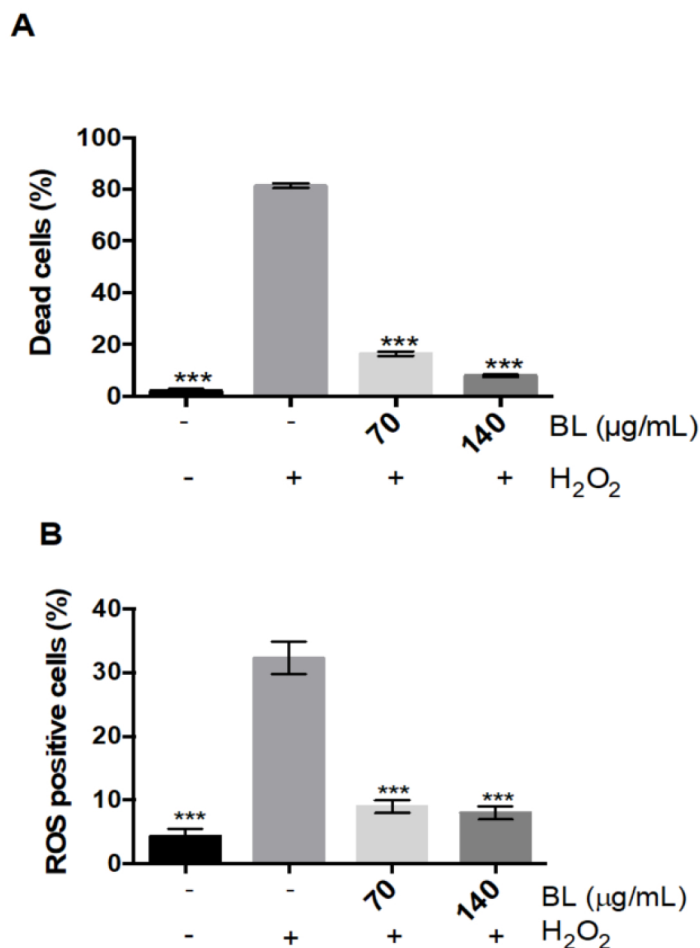


Figure 1. *A. lappa* leaves extract protects human myoblasts from induced oxidative stress. Cell death (A) and ROS (B) quantification (percentage of all cells) in human myoblasts that were incubated with the *A. lappa* leaves extract (BL) at indicated concentrations prior to incubation with H_2O_2 . All data represent the means \pm SD of three independent experiments; $p < 0.001$ (***) compared with H_2O_2 (one-way ANOVA).

A bioassay-guided fractionation method combining a precipitation step with MeOH and CH_2Cl_2 as solvents and chromatography steps using LH 20 Sephadex and silica gels (see Materials and Methods 3.5 and Diagram S1 in Supplementary Data) was used to identify the compound(s) responsible for the antioxidant activity of the *A. lappa* leaves extract. After four steps of purification a pure antioxidant compound was obtained (Diagram S1 in Supplementary Data and Figure 2). The structure was elucidated by NMR (Table S1 in Supplementary Data) as onopordopicrin, previously described in *A. lappa* [30–32]) and other Asteraceae [33–35].

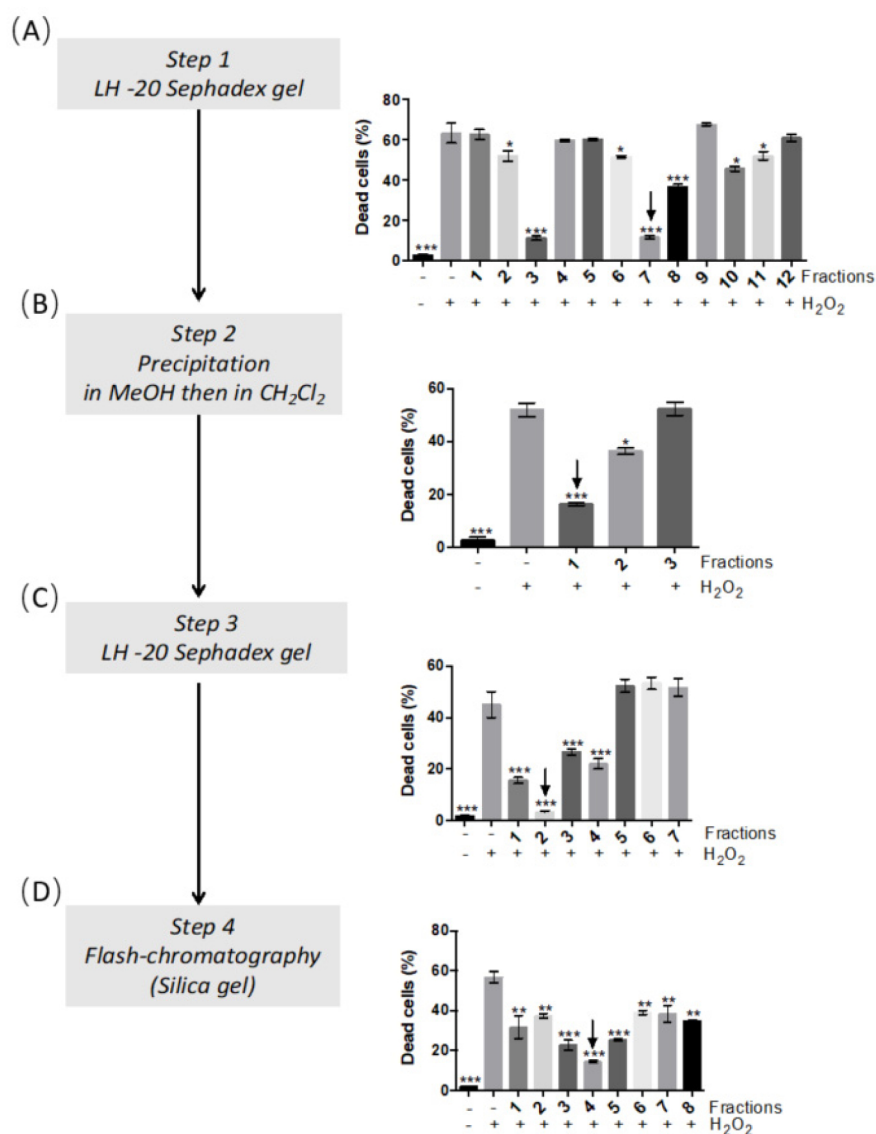


Figure 2. Bioassay-guided isolation of the antioxidant compound from the *A. lappa* leaves extract (BL extract). On the left: each step of the BL extract purification; on the right: the associated bioassay on myoblasts with the fractions obtained from the different steps of purification. Cell death quantification (percentage of all cells) in human myoblasts incubated with BL extract fractions at 1 $\mu\text{g}/\text{mL}$ (step 1 (A) and 2 (B)) or 0.5 $\mu\text{g}/\text{mL}$ (step 3 (C) and 4 (D)) prior to incubation with H₂O₂. All data represent the means \pm SD of three independent experiments; $p < 0.05$ (*) $p < 0.01$ (**) $p < 0.001$ (***) compared with H₂O₂ (one-way ANOVA).

2.2. Antioxidant Capacity of the Sesquiterpene Lactone Onopordopicrin

2.2.1. Onopordopicrin Protects Human Myoblasts against H₂O₂-Induced Stress

Before assessing onopordopicrin antioxidant activity, increasing concentrations of this molecule were incubated for 24 h with myoblasts to evaluate its cytotoxicity. We first measured the viability of cells (Figure 3A) and the accumulation of ROS (Figure 3B), highly reactive molecules associated with apoptotic cells. Based on both graphics (Figure 3A,B), we observed that onopordopicrin was toxic starting from 1 $\mu\text{g}/\text{mL}$ with a decrease in cell viability and an increase in ROS quantity. Therefore, to avoid cytotoxicity we chose to incubate myoblasts with 0.125 $\mu\text{g}/\text{mL}$, 0.25 $\mu\text{g}/\text{mL}$ and 0.5 $\mu\text{g}/\text{mL}$ of onopordopicrin to perform the antioxidant assay on myoblasts. Data on Figure 3C indicate that pretreatment with onopordopicrin, concentrations ranging from 0.125 to 0.5 $\mu\text{g}/\text{mL}$, inhibited the H₂O₂-mediated loss of myoblast cell viability. We further determined whether onopordopicrin can abolish H₂O₂-induced DNA damage by analyzing the phosphorylation of

γ H2AX (p - γ H2AX), a protein phosphorylated upon the DNA double-strand break. As shown in Figure 3D the protein expression of p - γ H2AX in cells treated with H_2O_2 alone drastically increased. However, pretreating the cells with onopordopicrin at 0.25 μ g/mL and 0.5 μ g/mL reduced the H_2O_2 -induced phosphorylation of γ H2AX, indicating that onopordopicrin blocked DNA damages due to oxidative stress.

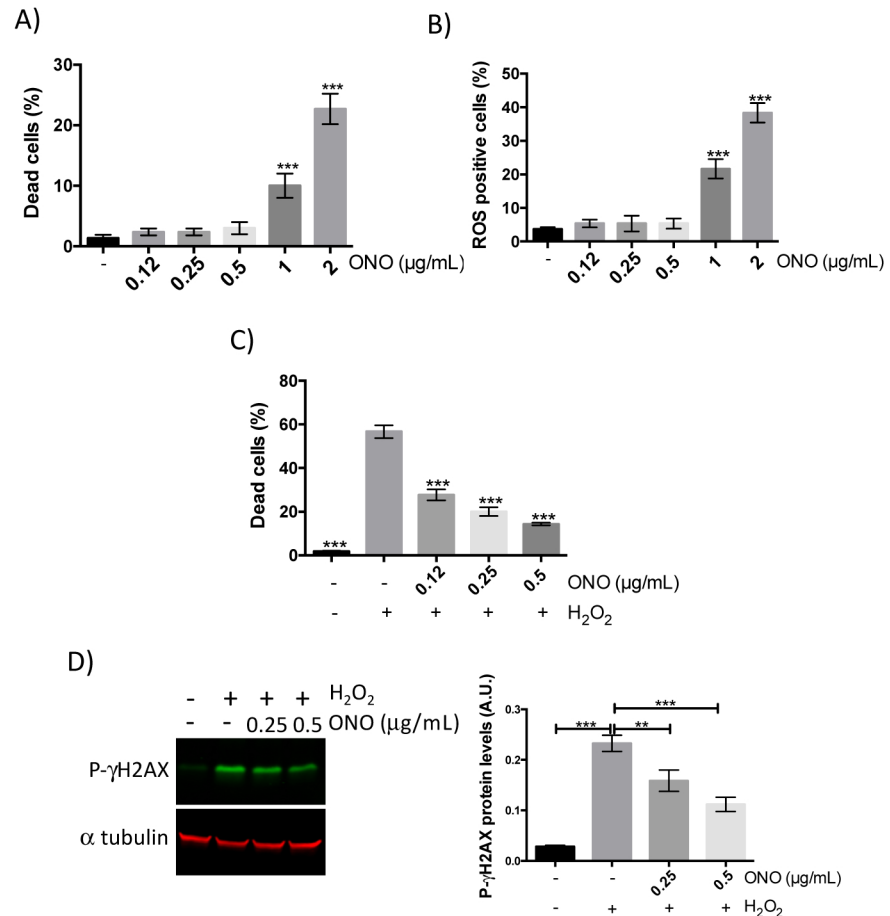


Figure 3. Onopordopicrin has a strong antioxidant activity on human muscle cells. Cell death (A,C) and reactive oxygen species (ROS) (B) quantification (percentage of all cells) in human myoblasts treated with onopordopicrin (ONO) at indicated concentrations prior to incubation with lethal concentration of H_2O_2 ; (D) human myoblasts treated with onopordopicrin (ONO) at indicated concentrations prior to incubation with sub-lethal concentration of H_2O_2 . On the left, Western blot analysis of phosphorylated γ H2AX protein level; on the right, quantification of the Western blot data, A.U. for arbitrary unit represents the ratio of p - γ H2AX protein level on α tubulin protein level. All data represent the means \pm SD of three independent experiments; $p < 0.01$ (**) $p < 0.001$ (***) compared with H_2O_2 in A, B and C (one-way ANOVA).

2.2.2. Onopordopicrin Activates the Nrf2/HO-1 Signaling Pathway

To overcome oxidative stress, cells have several antioxidant defense mechanisms to maintain ROS at low physiological levels. One of them is the modulation of the nuclear factor erythroid-2-related factor 2 (Nrf2), a transcription factor that could mediate genes encoding drug transporters, antioxidants enzymes, anti-apoptotic proteins and detoxifying factors [36]. It is known that Nrf2 plays a protective role against oxidative stress through regulating anti-oxidative genes, such as heme oxygenase-1 (HO-1) [37]. Thus, we have evaluated whether the antioxidant activity of onopordopicrin was correlated with the activation of the Nrf2/HO-1 signaling pathway. By analyzing immunoblotting data, we found that the expression of HO-1 protein was upregulated in myoblasts treated with the onopordopicrin sample compared with untreated cells (Figure 4A). These results suggest

that onopordopicrin can act as an activator of Nrf2 signaling pathway in myoblasts. Then, we investigated whether the Nrf2 signaling pathway was involved in the protection of onopordopicrin against H₂O₂-induced oxidative stress by using Nrf2 siRNA. We tested two Silencer Select siRNA of Nrf2, siNrf2-91 and siNrf2-93. siRNA 91 was the most effective in inhibiting Nrf2 (80% inhibition) and its target HO-1 (60% inhibition), and was therefore used for the following experiments (Figure 4B). We first tested the effect of dimethylfumarate (DMF), a well-known activator of Nrf2 pathway [38]. Figure 4C shows that DMF treatment protects myoblasts from H₂O₂-induced cell death. This protecting effect was lost in Nrf2 siRNA-transfected cells. Similarly, by pretreating myoblasts with onopordopicrin, we were able to protect cells with siRNA negative control (siCTRL) but not siNrf2 cells from H₂O₂-induced apoptosis (Figure 4D). In contrast, Tempol, a powerful synthetic antioxidant acting through the direct chelation of free radicals [39], reduced the number of dead cells both in siCTRL and in siNrf2 transfected cells treated with H₂O₂ (Figure 4D). These results demonstrate that onopordopicrin activates Nrf2/HO-1 signaling pathway in H₂O₂-treated myoblasts alleviating oxidative stress and improving oxidant resistance.

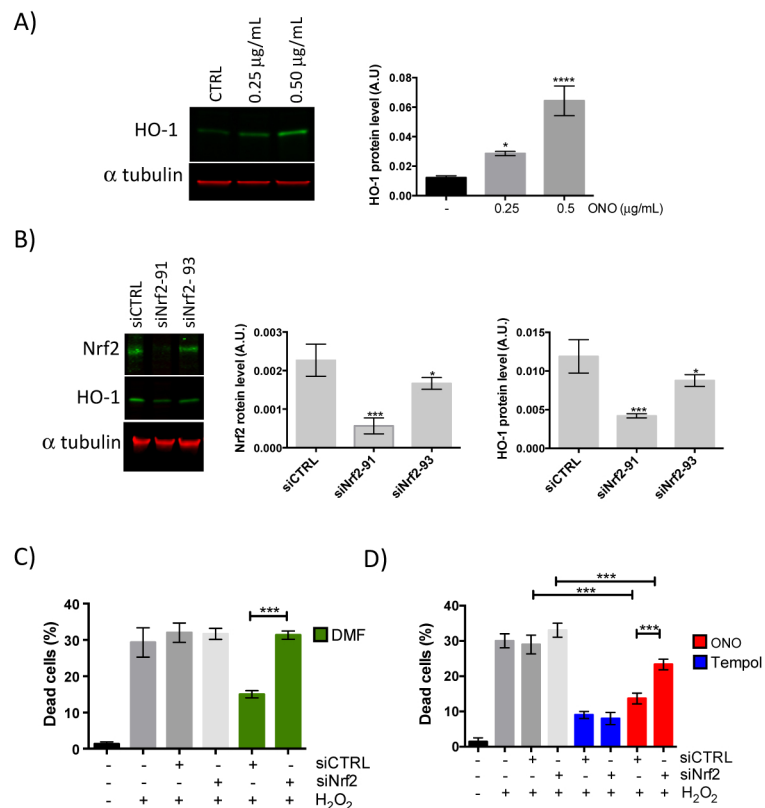


Figure 4. Onopordopicrin activates the Nrf2/HO-1 signaling pathway. (A) On the left, Western blot analysis of HO-1 protein level in human myoblast treated with onopordopicrin during 24 h at the indicated concentrations; CTRL: cells not incubated with onopordopicrin; on the right, quantification of Western blot data, A.U. for arbitrary unit represents the ratio of HO-1 protein level on α tubulin protein level. (B) On the left, Western blot analysis of HO-1 and Nrf2 levels in human myoblasts transfected with siNrf2-91 and siNrf2-93; on the right, quantification of the Western blot data, A.U. for arbitrary unit represents the ratio of Nrf2 and HO-1 protein levels on α tubulin protein level. (C,D). Cell death quantification (percentage of all cells) in human myoblasts transfected with Nrf2 siRNA or with siRNA negative control (siCTRL) and treated with dimethylfumarate (DMF) (20 μ M) or Tempol (50 μ M) or onopordopicrin (0.5 μ g/mL) prior to incubation with H₂O₂. All data represent the means \pm SD of three independent experiments; $p < 0.05$ (*) $p < 0.001$ (***) $p < 0.0001$ (****) compared to untreated cells in A and compared to siCTRL in B (one-way ANOVA).

3. Discussion

In this study, we identified and characterized a molecule extracted from burdock leaves, onopordopicrin, as being a molecule with strong antioxidant activity in human muscle cells. *Arctium lappa*, a well-known traditional medicinal plant contains compounds that have shown many bioactive properties, such as anti-inflammation, antioxidant, anti-microbial, anti-viral and anticarcinogenic effects [22]. Previous studies, made with in vitro assays such as the DPPH assay, have provided evidence for the antioxidant activity of *A. lappa* leaves [26,27]. It has been suggested that the phenolic and flavonoid content present in the leaf extracts could be responsible for the antioxidant activity [27]. In our study, we used a bioassay-guided fractionation method to identify antioxidant compounds from an *A. lappa* leaves extract. Surprisingly, the main antioxidant able to protect the H₂O₂-treated myoblasts we identified was not a phenolic or flavonoid compound but a molecule called onopordopicrin belonging to the family of sesquiterpene lactones. Initially, onopordopicrin has been reported as a constituent in leaves of *Onopordum acanthium* [33]. This molecule has also been previously isolated from *A. lappa* leaves [30–32] and from aerial parts of *Arctium nemorosum* and *Onopordum illyricum* [34,35]. Sesquiterpene lactones are lipophilic secondary metabolites abundant in plants of the Asteraceae family. These molecules have been reported to possess a broad spectrum of biological activities including anti-inflammatory, phytotoxic, antibacterial, antiplasmodial, antioxidant and cytotoxic/anticancer properties [31,35,40–46]. In this study, we demonstrated that onopordopicrin was able to prevent myoblasts from oxidative stress leading to an increase in cell viability, decrease in ROS production and DNA cellular damages. Previously, we showed that taxodione, a diterpene extracted from stems of *Rosmarinus officinalis*, could protect human myoblasts against H₂O₂-induced oxidative stress damage [47]. We also demonstrated that taxodione is as effective as butylated hydroxytoluene (BHT), a synthetic antioxidant, in limiting lipid and protein oxidation in post mortem mouse and beef muscles [47]. We tested onopordopicrin in similar conditions to see if this molecule could reduce oxidation during the refrigerated storage of meat but no protection of lipids and proteins against oxidation has been observed (unpublished observations). These results suggest that onopordopicrin may not share the mechanisms of taxodione and BHT such as the direct chelation of free radicals to prevent muscle cells from oxidative stress. Onopordopicrin could be useful in the treatment of degenerative muscle diseases. Oxidative stress has been implicated in several skeletal muscle degenerative diseases, such as Duchenne muscular dystrophy (DMD), facioscapulohumeral dystrophy (FSHD), laminopathy and dystrophies related to mutation in collagen VI and dysferlin genes [6]. In addition, high oxidative stress could limit the effectiveness of therapeutic approaches in skeletal muscle [48–52]. The failure of cell therapy in initial clinical trials was mainly attributed to poor survival rates of transplanted myoblasts [53–56]. There is an interesting correlation between the redox status of myoblasts and their effectiveness in regenerating muscle tissue. Myoblasts are characterized by enhanced ROS levels, reduced levels of antioxidant and detoxifying enzymes and an increased sensitivity to oxidative stress [57]. The pre-treatment of myoblasts with antioxidant molecules improves graft survival and would be an interesting strategy to improve cell transplantation therapy ([49–51]).

Onopordopicrin isolated from *Onopordum illyricum* was shown to act as a potent inhibitor of the pro-inflammatory transcription factors NF- κ B and STAT3. In addition, onopordopicrin was reported to enhance the activity of Nrf2, quantified using the HaCaT-ARE-Luc reporter gene suggesting a potential role of onopordopicrin on the expression of Nrf2 gene, the main regulator of the cellular antioxidant response [35]. Under stress conditions, Nrf2 uncouples from its endogenous inhibitor Kelch-like ECH-associated protein 1 (Keap1). Then, Nrf2 enters the nucleus and binds its cognate response element, the antioxidant response element (ARE), which upregulates the transcription of ARE-responsive genes, such as HO-1 or NQO1 (quinone oxidoreductase 1) having the ability to protect cells against oxidative stress. Thus, in this study, we investigated whether onopordopicrin could activate the endogenous Nrf2 signaling pathway in primary human

muscle cells. By using siRNA, we demonstrated that the inhibition of Nrf2 reduces the expression level of Nrf2 downstream target protein HO-1 and abolishes the protective effect of onopordopicrin in muscle cells. These results indicate that the activation of the Nrf2/HO-1 signaling pathway mediates the antioxidant effect of onopordopicrin in primary human muscle cells.

The activation of the Nrf2/HO-1 signaling pathway by onopordopicrin is a characteristic shared by other sesquiterpene lactones. For instance, the two sesquiterpene lactones hemisteptin A from *Hemistepta lyrata* and alantolactone from *Inula helenium* have been shown to activate the Nrf2/HO-1 pathway and to protect against oxidative stress in human keratinocytes and bronchial epithelial cells, respectively [45,58]. Another sesquiterpene lactone, parthenolide, found in feverfew (*Tanacetum parthenium*) and belonging, like onopordopicrin, to the germacrane subclass, was shown to have antioxidant properties by increasing the expressions levels of Nrf2 and HO-1 in H₂O₂-treated osteoblasts [59]. In a more recent study, it was demonstrated that parthenolide could also inhibit obesity and obesity-induced inflammatory responses in vitro and in vivo models. For the in vivo study, the authors used a model of high-fat diet (HFD)-fed mice to show that the administration of parthenolide induced a reduction in body weight and white adipose tissues. Moreover, they demonstrated that the parthenolide-mediated anti-obese effect was connected to anti-inflammatory responses with the regulation of inflammatory cytokines. In addition, they showed that parthenolide suppressed HFD-mediated oxidative stress by regulating the level of antioxidant molecules via the activation of the Nrf2 signaling pathway [60]. Thus, it seems that an increasing number of recent studies demonstrated the activation of Nrf2 by sesquiterpene lactones like onopordopicrin but how these molecules can activate Nrf2 is still not well understood. It is believed that the methylene- γ -lactone group of sesquiterpene lactones is the main responsible for biological activities as anti-inflammatory [35,61], cytotoxic [34] or antitrypanosomal [34]. Indeed, the methylene- γ -lactone group can react as a thia-Michael acceptor. Moreover, the opening of the γ -lactone is associated with a decrease in Nrf2 activation [35]. The 2-(hydroxymethyl)acrylate side chain represents a second Michael acceptor site in the structure of onopordopicrin. This chain seems to be important for activities [34,61], but it appears to be less reactive than the methylene- γ -lactone group in NMR-based cysteamine assay [35]. For onopordopicrin, thia-addition is observed quickly and only on the methylene- γ -lactone group, whereas for carmanin, a sesquiterpene without lactone, the addition was made on the 2-(hydroxymethyl)acrylate side chain very slowly [35]. Moreover, costunolide, a sesquiterpene lactone without a side chain, was an effective Nrf2 activator in PC12 cells [62] and finally elevated the protein expression of NQO1 (quinone oxidoreductase 1), TrxR (thioredoxin reductase), Trx (thioredoxin) and HO-1. This suggests that a Michael addition reaction between the methylene- γ -lactone group in costunolide and the cysteine residue in Keap1 is responsible for the activation of Nrf2 [62]. The same mechanism can occur with onopordopicrin in muscle cells. Further experiments with a large panel of sesquiterpenes could confirm that the methylene- γ -lactone group is the major site for the activation of Nrf2. The role of the 2-(hydroxymethyl) acrylate side chain could be determined for the reaction with Keap1.

In addition to their antioxidant and anti-inflammatory activities, sesquiterpene lactones have been shown to have cytotoxic/anticancer effects. In this context, parthenolide is one of the most studied sesquiterpene lactones and is considered as a potential antitumoral agent [63]. Sesquiterpene lactones have been shown to inhibit proliferation, induce apoptosis, promote cell cycle arrest and inhibit metastasis [64]. These processes would result from the disruption of the cellular redox balance and induction of oxidative stress in cancer cells [63]. In our study we showed that onopordopicrin, at concentrations superior to 0.5 $\mu\text{g}/\text{mL}$, induced ROS accumulation and cell cytotoxicity (Figure 3A,B), demonstrating that onopordopicrin can act as a pro-oxidant under certain conditions at high concentrations. These results are in agreement with a previous study showing that onopordopicrin has antiproliferative activity in tumor cells [31]. Therefore, it would be

