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Proteomic analysis of F_1F_0-ATP synthase super-assembly in mitochondria of cardiomyoblasts undergoing differentiation to the cardiac lineage

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ABSTRACT

Mitochondria are essential organelles with multiple functions, especially in energy metabolism. An increasing number of data highlighted their role for cellular differentiation processes. We investigated differences in ATP synthase supra-molecular organization occurring in H9c2 cardiomyoblasts in the course of cardiac-like differentiation, along with ATP synthase biogenesis and maturation of mitochondrial cristae morphology. Using BN-PAGE analysis combined with one-step mild detergent extraction from mitochondria, a significant increase in dimer/monomer ratio was observed, indicating a distinct rise in the stability of the enzyme super-assembly. Remarkably, sub-stoichiometric mean values for ATP synthase subunit e were determined in both parental and cardiac-like H9c2 by an MS-based quantitative proteomics approach. This indicates a similar high proportion of complex molecules lacking subunit e in both cell types, and suggests a minor contribution of this component in the observed changes. 2D BN-PAGE/immunoblotting analysis and MS/MS analysis on single BN-PAGE band showed that the amount of inhibitor protein IF_1 bound within the ATP synthase complexes increased in cardiac-like H9c2 and appeared greater in the dimer. In concomitance, a consistent improvement of enzyme activity, measured as both ATP synthesis and ATP hydrolysis rate, was observed, despite the increase of bound IF_1 evocative of a greater inhibitory effect on the enzyme ATPase activity. The results suggest i) a role for IF_1 in promoting dimer stabilization and super-assembly in H9c2 with physiological IF_1 expression levels, likely unveiled by the fact that the contacts through accessory subunit e appear to be partially destabilized, ii) a link between dimer stabilization and enzyme activation.

1. Introduction

Most of the cell energy is provided by mitochondria in the form of ATP through oxidative phosphorylation, whose final step is catalyzed by transmembrane ATP synthase (F_1F_0-ATP synthase) [1]. In bacteria, chloroplasts, and mitochondria, this enzyme functions to harness the energy of a transmembrane proton-motive force for ATP biosynthesis [2]. Its energy-coupling mechanism involves a rotary motion of the central stalk of the F_1F_0-complex driven by H^+ conduction through F_0 in the forward ATP synthesis direction, and an opposite H^+-pumping rotation backward driven by the free energy change of ATP hydrolysis [3–7]. In membranes, ATP synthase exists as a native functional dimer assembled to form long rows of oligomers [8]. Such ATP synthase self-association occurring constitutively in mitochondria promotes membrane curvature and formation of proper mitochondrial cristae ultrastructure [9–14]. In mammals, fewer data are available and the first projection structure of dimeric ATP synthase was solved by means of transmission electron microscopy and image analysis of the dimeric enzyme extracted from bovine heart in the presence of digitonin [15]. ATP synthase super-assembly is also considered to play a critical role in maintaining a high transmembrane potential, which ensures optimal conditions for an efficient ATP synthesis [8,16]. Consistently, increase in

Abbreviations: ATP synthase, F_1F_0-ATP synthase; BN-PAGE, blue native polyacrylamide gel electrophoresis; hrCN-PAGE, high resolution clear native polyacrylamide gel electrophoresis; IF_1, mitochondrial inhibitor protein; DMEM, Dulbecco's modified Eagle's medium; FCS, fetal calf serum; RA, all-trans-retinoic acid; C, parental H9c2 cells; D, differentiation-committed H9c2 cells; PBS, phosphate buffered saline; EDTA, ethylenediaminetetraacetic acid; Tris, tris (hydroxymethyl)aminomethane; EGTA, ethylene glycol-bis(β-aminoethylether)-N,N,N′,N′-tetraacetic acid; SDS, sodium dodecyl sulfate; Vm, F_1F_0-ATP synthase monomer; Vd, F_1F_0-ATP synthase dimer; Vo, F_1F_0-ATP synthase oligomer; SRM, Selected Reaction Monitoring mode; nanoLC–ESI-LIT-MS/MS, nano-liquid chromatography–electrospray-linear ion trap-tandem mass spectrometry; MS, mass spectrometry

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ATP synthesis was documented concomitant with increase in the formation of dimeric ATP synthase complexes also in mammalian cell lines [17]. In addition, by native electrophoresis analysis combined with in gel-activity measurements of bovine heart mitochondrial extracts we demonstrated that the ATPase activity of the enzyme dimer is greater than that of monomer at physiological temperature [18].

The overall structure of the mitochondrial ATP synthase monomer is well conserved from bacteria to humans. This enzyme is a multi-subunit complex formed by two functionally and physically coupled portions with dual genetic origin. Thus, ATP synthase biogenesis is a sophisticated process that depends on the coordinated expression of nuclear and mitochondrial genomes [19]. This enzyme presents a hydrophobic domain, F_0 (c-ring and a subunits), containing a H^+ channel, and a hydrophilic domain, F_1 ($\alpha_3\beta_3$ subunits), bearing the adenine nucleotide processing sites. F_0 and F_1 domains are connected by the so-called central (γ, δ, and ε subunits) and peripheral (b, d, OSCP, F6, A6L subunits) stalks [20]. Accessory subunits, which vary in different species, contribute to enzyme structure, regulation and supra-molecular organization. Their role in supra-molecular organization has been unveiled by native gel electrophoresis of the homodimeric enzyme, proteomic identification of dimer-specific subunits, and genetic deletion experiments in yeast, where removal of subunits e and g lead to a loss of the dimeric/oligomeric structures, together with a modification of mitochondrial cristae morphology [10,21–23]. A selective proteolysis approach applied to bovine heart mitoplasts allowed us to demonstrate a role of subunit e in dimer/oligomer stability even in mammals [24]. In addition, self-association of ATP synthase complexes was proved to occur through subunits of the lateral stalk [25,26] and subunits a and c of the F_0 sector [27], but the nature of the interface domains in monomeric/dimeric forms is still debated. In this context, the first 3D view by transmission electron microscopy at 27 Å of the yeast ATP synthase dimer [28] showed the existence of a narrow angle between monomers, in accordance with the first 2D image of the dimeric enzyme extracted from bovine heart [15]. On the other hand, three-dimensional maps of the ATP synthase dimer obtained using electron cryotomography of bovine [14] and yeast [29] mitochondrial membranes, revealing a V-shaped structure with a wider angle of 86° between monomers, have been reported more recently. The protein interface between monomers which interact within the membrane at the base of the peripheral stalks is elucidated, whereas the self-organization of ATP synthase dimers into rows, that is a requisite for normal cristae morphology, is reported as occurring without the need for direct protein contacts through dimers based on the highly variable distances and angles between dimers in a row [29]. Consistently, by large-scale molecular dynamics simulations the authors proposed that reduction in elastic energy of the membrane deformation caused by individual dimer is sufficient to drive the self-assembly of dimers into rows, thus emphasizing the key role of dimers in mitochondria morphology.

In mammals, endogenous mitochondrial inhibitor protein IF_1 [30], which plays a prominent role in enzyme activity regulation both in vitro and in vivo [31,32], has also been suggested to promote ATP synthase dimerization by formation of IF_1–IF_1 bridge [33]. Accordingly, it has been found that over- or reduced expression of IF_1 promotes or diminishes cristae formation in the mitochondria of cultured mammalian cells, respectively [17]. Recently, the atypical morphology of the syncytiotrophoblast mitochondria has been shown to correlate with a low content of dimeric enzyme and of IF_1, thus confirming a key role played by these elements in determining cristae shape in human placental mitochondria [34]. Nevertheless, whether or not IF_1 actually takes part in promoting ATP synthase dimerization still remains to be definitively demonstrated as dimer was observed in some cases even without bound IF_1 [35–37].

Cell energy demand changes dramatically during development and differentiation, and mitochondrial content and function can be adjusted to suit the current cellular status [38]. Thus, mitochondrial biogenesis is included in differentiation program to face phenotypes characterized by high energy demand, as for skeletal and cardiac myocytes. It was reported that, concomitant with mitochondrial biogenesis, coordinated changes in the metabolic enzymes of oxidative phosphorylation occur during myogenesis [39] and a significant increase in mitochondrial ATP synthase, including α and β subunits, is associated with adipogenesis [40]. Mitochondrial remodeling in term of maturation and network expansion occurs during cardiac differentiation of stem cells and cardiomyoblasts [41–43]; this process is considered as an essential mechanism toward the execution of the cardiac differentiation program [41,42]. In accordance, a recent analysis of different cardiac mesoangioblast populations illustrates that mitochondrial content in mesoangioblasts can have significant effects on their downstream potential for cardiac differentiation, and suggests that mitochondrial load could be utilized in a selection regime to purify the best candidates from a polyclonal population, for transplantation studies [44].

This study was aimed at investigating the ATP synthase supramolecular organization changes related to the mitochondrial biogenesis, and occurring in particular in H9c2 cardiomyoblasts committed to differentiation towards the cardiomyocyte lineage. Recently, we observed that organelle biogenesis concomitant with H9c2 cardiac-like differentiation involves a mass increase, changes in shape/structure (resulting in closely packed mitochondrial cristae), increased ATP synthase activity and augmented phosphorylating respiration, as well as enhanced whole F_1F_0-complex biogenesis [43]. By using blue native electrophoresis (BN-PAGE) [45] and MS-based proteomic analyses, here we have obtained evidence that ATP synthase super-assembly in mitochondria is also enhanced in cardiac-like differentiating H9c2, and that IF_1 plays a role in dimer stabilization. Such a role is probably unveiled by the fact that the monomer–monomer contacts through the accessory subunit e are partially destabilized. Dimer stabilization is accompanied by enzyme activation, through a mechanism still to be clarified, and is considered as a pre-requisite for the changes observed in cristae ultrastructure by favoring dimer rows formation.

2. Materials and methods

2.1. Cell cultures and differentiation treatments

Clonal cell line H9c2 was obtained from American Type Culture Collection (CRL-1446). Cells were grown at a density of about 10^5 cells/cm^2 as monolayer in Dulbecco's modified Eagle's medium (DMEM) high glucose (Euroclone, Devon, UK), supplemented with 10% v/v fetal calf serum (FCS), 2 mM L-glutamine, penicillin (100 μU/ml), streptomycin (100 μg/ml) and gentamycin (10 μg/ml) (all from Euroclone). Subconfluent cells were committed to differentiate into the cardiomyocyte lineage by culturing in the presence of low serum (1% FCS) and 10 nM all-*trans*-retinoic acid (RA) (Sigma, St. Louis, MO, USA) [46]. Treatment was prolonged for at least 14 days [43]. Throughout treatment, the expression level of cardiac markers was evaluated to monitor the differentiating effects elicited and optimize the protocol reproducibility. Specifically, immunofluorescence microscopy was used with commercial antibodies for troponin 1 cardiac isoform (mouse monoclonal antibody, Abcam, Cambridge, UK), myosin heavy chain MHC (goat polyclonal antiboby, Santa Cruz Biotechnology Inc., Santa Cruz, CA, USA) and α-sarcomeric actin (mouse monoclonal antibody, Sigma). No positive signal for all the investigated markers was observed in the parental line.

2.2. Mitochondria isolation

Subconfluent parental (C) or differentiation-committed (D) cells were washed in phosphate buffered saline (PBS) (8.1 mM Na_2HPO_4, 1.4 mM KH_2PO_4, 137 mM NaCl, pH 7.4), proteolyzed with trypsin–

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EDTA, centrifuged at 400 ×*g* for 5 min, at 25 °C, and suspended in homogenization buffer (250 mM sucrose, 10 mM Tris/HCl and 0.1 mM EGTA, pH 7.4), supplemented with 1:10 Sigma protease inhibitor cocktail (cat. P8340). Cell suspensions, at a concentration of 2×10^7 cells/ml, were sonicated in a ice-cold bath, attaining about 95% of disrupted cells. Mitochondria were isolated as described previously [43]. Briefly, cell homogenates were subjected to centrifugation (800 ×*g* for 12 min, at 4 °C) to remove intact cells, nuclei, and large cell debris. Pellets were washed for a total of three times, and the final supernatants were collected and centrifuged at 16,000 ×*g* for 20 min, at 4 °C, to obtain mitochondrial pellets. Mitochondria were finally suspended in isotonic buffer and immediately used or frozen at −80 °C and stored until further use. Protein content was determined according to the Lowry method [47].

2.3. Enzyme activity assays

2.3.1. ATP synthase

The rate of ATP synthesis catalysed by the mitochondrial ATP synthase was measured monitoring the increase in absorbance at 340 nm using a hexokinase: glucose-6-phosphate dehydrogenase coupled enzyme system as in [43]. Briefly, freshly isolated intact mitochondria were suspended in 20 mM glucose, 10 mM HEPES pH 7.5, 50 mM KCl, 5 mM $MgCl_2$, 10 mM KH_2PO_4, 10 mM potassium succinate, 20 UI/ml hexokinase, 22 UI/ml mM glucose-6-phosphate dehydrogenase, 1.5 mM $NADP^+$, 30 U/ml lactate dehydrogenase (Boehringer Mannheim, Mannheim, Germany), 40 U/ml pyruvate kinase (Boehringer Mannheim) and allowed to incubate with gentle shaking at room temperature for 3 min. 20 mM P–P diadenosine-5′ pentaphosphate was also present to inhibit contaminant adenylate kinase. The reaction was initiated by adding Tris-buffered ADP (final concentration 5 mM). The selective measurement of ATP synthase activity was ensured on the basis of sensitivity to 10 μM oligomycin.

The rate of ATP hydrolysis catalysed by ATP synthase was measured following the decrease in absorbance at 340 nm, by using the pyruvate kinase: lactate dehydrogenase coupled ATP-regenerating enzyme system, as in [43]. Briefly, freshly-isolated mitochondria were osmotically shocked by 5-fold dilution in distilled water and incubated with 30 mM sucrose, 50 mM Tris–HCl (pH 7.4), 50 mM KCl, 2 mM EGTA, 4 mM $MgCl_2$ and 4 μM rotenone, for 15 min under gentle shaking. 2 mM phosphoenol pyruvate, lactate dehydrogenase (Boehringer, Mannheim) (30 U/ml), pyruvate kinase (Boehringer Mannheim) (40 U/ml) and 0.3 mM NADH were then added to the assay mixture and allowed to incubate for 3 min, at 25 °C, with gentle shaking. Reaction was initiated by adding Tris-buffered ATP (2 mM final concentration). Interferences by contaminant Ca^{2+}- and Na^+/K^+-ATPases were minimized due to the composition of the buffer (containing EGTA and <5 mM Na^+), as verified in the presence of the specific inhibitors, sodium orthovanadate or ouabain [48]. To further prove the specificity of ATPase activity of mitochondrial ATP synthase, aurovertin (2 μM) inhibitor was routinely used in control assays. 10 μM oligomycin was used to determine the oligomycin-sensitive ATPase activity, which corresponds to the activity of the correctly assembled F_1F_0-complex, able to synthesize ATP.

Activities were expressed as Units (μmol/min) per mg protein, and normalized to citrate synthase activity as a measure of specific activity

2.3.2. Citrate synthase

The assay was performed spectrophotometrically as described previously [43]. Briefly, isolated mitochondria were permeabilized by sonication and added to the assay buffer (0.1 mM 5,5′-dithiobis-2-nitrobenzoic acid, 0.3 mM acetylCoA and 0.5 mM oxalic acid). The increase in absorbance at 412 nm was measured with a reference cuvette lacking oxalacetate to correct for background thiolase activity. Activity was expressed as Units (μmol/min) per mg protein.

2.4. Gel electrophoretic and immunoblotting analyses

2.4.1. Sample preparation and native electrophoresis

Isolated mitochondria were diluted at the final protein concentration of 15 mg/ml in solubilization buffer (50 mM NaCl, 5 mM 6-aminocaproic acid and 30 mM Tris–HCl pH 7.4). Samples were solubilized with digitonin (Fluka, St. Louis, MO, USA) using a detergent to protein ratio ranging from 2 to 7 w/w in a final volume of 40 μl; they were immediately centrifuged at 100,000 ×*g* for 25 min, at 4 °C, recovering the soluble fraction. Protein concentration was determined according to the Bradford method [49]. Supernatants were supplemented with Coomassie blue G-250 (Serva, München, Germany) and BN-PAGE was carried out in gradient gels (4–11% acrylamide) according to previous studies [18,45]. Gels were stained with Coomassie blue G-250 or with *in-gel* activity staining [18], or subjected to immunoblotting (1D-BN-PAGE/immunoblotting), or to iterative SDS-PAGE-immunoblotting (2D BN-PAGE/SDS-PAGE/immunoblotting). Molecular mass of F_1F_0-ATP synthase dimeric (Vd) and monomeric (Vm) forms was estimated by using bovine heart mitochondria as a standard. The linearity of the band intensities observed after Coomassie staining and/or Western blot detection was verified by performing densitometric scanning of lanes loaded with increasing quantities of samples; ImageQuant, version 2003.03 (Amersham, Glattbrugg, CH) and Quantity One 4.2.1 (Bio-Rad, Berkeley, CA) software were used to this purpose.

2.4.2. In-gel ATPase activity staining

BN-PAGE lanes of interest were incubated in 35 mM Tris–HCl pH 7.4, 270 mM glycine, 14 mM $MgSO_4$, 0.2% w/v $Pb(NO_3)_2$, 8 mM ATP at 30 °C, overnight. ATP hydrolysis correlated with the development of a white lead phosphate precipitate. Gels were washed in water to stop the reaction and scanned by densitometry against a dark background.

2.4.3. Immunodetection of IF_1 in BN-PAGE-separated ATP synthase complexes and whole mitochondria

IF_1 immunodetection in whole mitochondria was performed by 1D-SDS-PAGE/immunoblotting. Mitochondria isolated from H9c2 cells were separated by 15% SDS-PAGE under reducing conditions [50] and analyzed for IF_1 and β subunits.

IF_1 immunodetection in ATP synthase complexes was achieved by 2D (BN-PAGE/SDS-PAGE) immunoblotting. Excised bands from BN-PAGE were separated by 2D glycine-SDS-PAGE under denaturing conditions using 15% polyacrylamide gels. Afterwards, proteins were stained with Coomassie Blue G-250 or analyzed for IF_1 and β subunits.

Gels were electrotransferred to nitrocellulose membrane (Biorad Hercules, CA, USA) using a semidry electroblotting system (Bio-Rad) and membranes were blocked in 20 mM PBS pH 7.4 containing 3% w/v non-fat dry milk (Bio-Rad) and 0.1% Tween 20 (Sigma). The antibodies used were anti-β subunit monoclonal antibody (1:1000 dilution, Abcam, Cambridge, UK) and anti-IF_1 monoclonal antibody (1:1000 dilution, Mitosciences, Eugene, Oregon, USA). Membranes were incubated with the primary antibody in PBS buffer, overnight, and washed thoroughly; immunoreactive bands were visualized by enhanced chemiluminescence assay (Pierce, Rockford, IL, USA) according to the manufacturer's instructions, using horseradish peroxidase-conjugated goat anti-mouse IgG (Pierce), at a dilution of 1:5000. Band intensities were measured by peak integration after densitometry analysis. For quantification purposes, calibration experiments were carried out by using purified bovine F_1 [51] and IF_1 [52], which were considered as proper standard proteins to determine IF_1–F_1 molar ratio in mitochondria from rat-derived cells, according to sequence homology criteria.

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2.5. Mass spectrometry analysis

2.5.1. Mass spectrometric quantification of IF_1 in BN-PAGE-separated ATP synthase complexes

For qualitative experiments, 1D BN-PAGE bands corresponding to dimeric (Vd) and monomeric (Vm) forms of ATP synthase, as purified from C and D cells, were *in-gel* reduced, S-alkylated and digested with sequencing-grade trypsin (Roche) (12.5 ng/μl), at 37 °C. Peptide digests were subjected to a desalting/concentration step on μZipTipC18 pipette tips (Millipore Corp., Bedford, MA, USA) and analyzed by nanoLC–ESI-LIT-MS/MS using a LTQ XL mass spectrometer (Thermo, USA) equipped with Proxeon nanospray source connected to an Easy-nanoLC (Proxeon, Odense, Denmark) [53]. For quantitative experiments, Vd and Vm bands were washed with 50 mM NH_4HCO_3, dehydrated in acetonitrile and digested with sequencing-grade endoprotease Lys-C (Roche) (20 ng/μl), at 37 °C. In this case, peptide digests were not subjected to a desalting step but directly analyzed by nanoLC–ESI-LIT-MS/MS, as reported above. In both cases, peptide mixtures were separated on an Easy C_{18} column (10 × 0.075 mm, 3 μm) (Proxeon) using a gradient of acetonitrile containing 0.1% v/v formic acid in aqueous 0.1% v/v formic acid; acetonitrile ramped from 5% to 40% over 40 min, from 40% to 80% over 10 min and from 35% to 95% over 2 min, at a flow rate of 300 nl/min. Spectra were acquired in the range m/z 400–2000. Acquisition was controlled by a data-dependent product ion scanning procedure over the three most abundant ions, enabling dynamic exclusion (repeat count 2 and exclusion duration 1 min). The mass isolation window and collision energy were set to m/z 3 and 35%, respectively.

Raw data files from nLC–ESI-LIT-MS/MS experiments were searched with both MASCOT (version 2.2.06, Matrix Science, UK) and SEQUEST programs, within the Proteome Discoverer software package (Thermo Fisher, USA, version 1.0 SP1), against an updated UniProtKB rat non-redundant (2011/10/17 version) and/or an optimized ATPase subunit sequence database. A mass tolerance value of 2 Da (for precursor ion) and 0.8 Da (for MS/MS fragments), trypsin or endoprotease Lys-C as proteolytic enzyme, a missed cleavages maximum value of 2 and Met oxidation and Cys carbamidomethylation (only for qualitative experiments) as variable and fixed modifications, respectively, were used to this purpose. Candidates with an individual MASCOT score > 25 and/or with an individual SEQUEST score vs. charge state (CS) > 1.5 for CS 1, >1.9 for CS 2, >2.4 for CS 3, >3.3 for CS 4, corresponding to $p < 0.05$ for a significant identification, were further evaluated.

A relative quantification of IF_1 in Vd and Vm from both D and C samples was obtained by extracting and integrating, in the same nLC–ESI-MS total ion chromatogram, peak areas corresponding to a selected peptide from subunit IF_1, and a selected peptide from subunit γ or two peptides from subunit β, which were used as invariant references. Extracted ion chromatograms were calculated for the range m/z 514.9–515.9, 657.4–658.4, 544.5–545.5 and 488.0–489.0 for peptide TREQLAALK (IF_1), ELIEIISGAAALD (γ), VVDLLAPYAK (β), and IGLFGGAGVGK (β), respectively. Peak areas were calculated by using the Genesis algorithm from Bioworks Qual Browser, version 2.0.7 (Thermo, USA). Relative percentage of IF_1 was then obtained by calculating the percentage ratio between peak area of IF_1 peptide and peak area of γ or β peptides.

2.5.2. Direct quantification of γ and e subunits in ATP synthase complexes in digitonin-extracted mitochondria

For each of the two subunits, γ and e, a proteotypic peptide was chosen, based on existing shotgun datasets (data not shown) acquired on an Orbitrap mass spectrometer (Thermo, Bremen, Germany). Peptides VYGTGSLALYEK and YSYLKPR for subunits γ and e, respectively, were chosen to this purpose and their isotopically labeled synthetic AQUA versions were obtained from ThermoScientific (Ulm, Germany). In each peptide the C-terminal K or R residue was substituted with the corresponding deuterated version having a mass shift of +8 or +10 Da, respectively. Prior trypsinolysis, a known amount of the internal standard peptides was added to the protein mixtures, which were extracted from mitochondria of C and D cells with digitonin (used at a detergent/proteins ratio 3:1 w/w). In solution digestion and peptide clean-up were performed as previously described [24]. Peptide mixtures were analyzed on a 5500 QTrap mass spectrometer (AB/Sciex, Toronto, Canada) equipped with a nanoelectrospray ion source, operating in Selected Reaction Monitoring mode (SRM). Chromatographic separation of peptides was performed on a Tempo Nano LC system (Eksigent, Dublin, CA) coupled to a 15 cm fused silica emitter, 75 μm diameter, packed with a Magic C_{18} AQ 5 μm resin (Michrom BioResources, Auburn, CA, USA). Peptides were loaded on the column from a cooled (4 °C) Eksigent autosampler and were separated with a linear gradient of acetonitrile/water, containing 0.1% formic acid, at a flow rate of 300 nl/min. A gradient from 5 to 30% acetonitrile in 30 min was used. Transitions corresponding to the doubly charged precursor of each peptide and all y-ions in m/z 400–1250 were monitored. Transitions corresponding to fragments with m/z values close to the precursor ion m/z (m/z_{Q1}–m/z_{Q3} ≤10 Th) were discarded. SRM acquisition was performed with Q1 and Q3 operating at unit resolution (0.7 m/z half maximum peak width) and with a dwell time of 60 ms/transition. Collision energy (CE) was calculated according to the formula: $CE = 0.044 * m/z + 5.5$. Peak height for the transitions associated with the standard and endogenous peptides was extracted manually. Absolute quantification was obtained by calculating the ratio between the height of the SRM peaks derived from the light and heavy version of each peptide; results were expressed as the mean out of the different SRM transition traces.

2.6. Statistical analysis

Data are reported as means ± SD or SE Intergroup comparisons were made with Student's t-test for two groups. A value of $p \leq 0.05$ was considered to be statistically significant.

3. Results and discussion

3.1. Monomeric and dimeric ATP synthase in mitochondria of parental and differentiating cardiomyoblasts

BN-PAGE analysis was used to compare the supra-molecular assembly of ATP synthase in mitochondria from H9c2 cells committed to cardiac differentiation by chronic treatment with RA (D), with respect to the parental line used as control (C). To this purpose, sample extraction with digitonin ensured mitochondria solubilization without disrupting protein super-assembly. In both cell types BN-PAGE analysis resolved ATP synthase in its dimeric (Vd) and monomeric (Vm) forms (Fig. 1a, *left*), with both forms having ATPase activity (Fig. 1a, *right*), while no higher oligomeric forms were detected. As the proportion of the dimeric enzyme in BN-PAGE is strongly dependent on the amount of detergent used for extraction, we carefully evaluated (by densitometry of Coomassie blue-stained gel) the amount of Vd and Vm in C and D cells by extracting corresponding mitochondria with solubilization buffers having different detergent-to-protein quantitative ratios (Fig. 1b). Thus, we monitored the efficiency of solubilization together with the detergent-sensitivity of Vd, which is indicative of the aggregation state in membrane. Digitonin used at a detergent/protein ratio of 3:1 w/w was chosen as the experimental condition suitable for a better dimeric protein recovery in both cell types. Unfortunately, oligomer band intensities were near to detection limits, even when *hr*CN-PAGE analysis was performed at lower digitonin/protein ratio (data not shown), and poor resolution was obtained, likely due to low amounts of oxidative phosphorylation complexes in mitochondria from our cells. In this respect, it should be highlighted that structure/stability of high order oligomers is a widely debated question. While numerous

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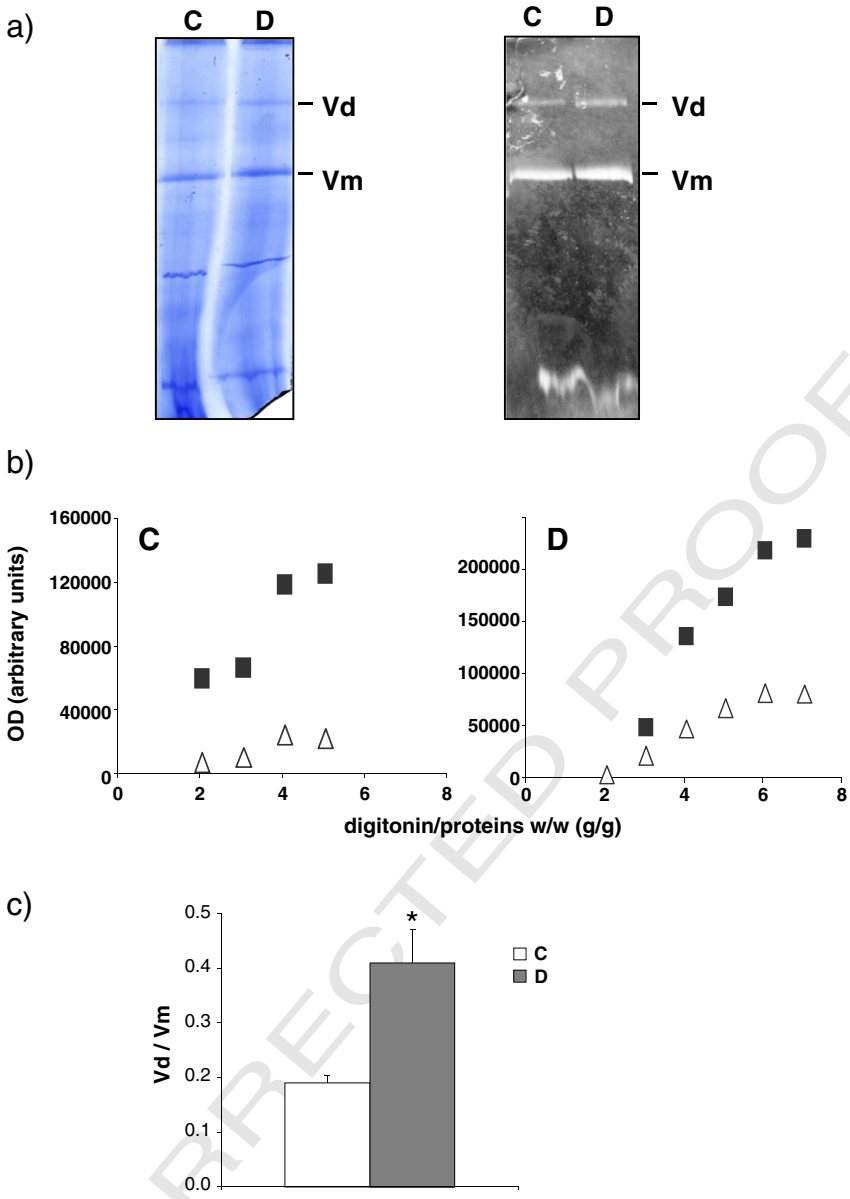

Fig. 1. Blue Native electrophoretic analysis of ATP synthase in control and differentiating mitochondria following extraction with digitonin. (a) Typical appearance of Coomassie blue G250-stained (*left*) and in-gel ATPase activity-stained BN-PAGE (*right*) of digitonin-extracted mitochondria. The position of ATP synthase dimeric (Vd) and monomeric forms (Vm) is indicated. This panel shows representative results from three independent experiments by performing digitonin extraction using a detergent/proteins ratio 3:1 w/w for both mitochondria types. (b) Mitochondria were treated with the indicated concentration of digitonin and analyzed by BN-PAGE. Values from densitometric analysis of dimer (Vd, empty triangle) and monomer (Vm, closed square) are reported (one experiment representative of three). Experimental condition for a better dimer recovery was detergent/mitochondrial proteins 3:1 w/w, which corresponded to minimal digitonin concentration to minimize monomer formation. (c) The dimer-to-monomer ratios (Vd/Vm), calculated from Coomassie blue-stained bands, are shown as a measure of the detergent-stability of Vd extracted with digitonin using a detergent/proteins ratio 3:1 w/w (white bar: mitochondria from parental control cells (C); gray bar: mitochondria from differentiation-committed cells (D). Values are the mean ± SE; $p \leq 0.01$ D vs. C, n = 3).

cross-linking studies supported the existence of a protein interface between dimers within oligomers, mainly through e/e and g/g subunits [54], evidence has been recently provided by electron cryotomography analysis of mitochondrial membranes and large-scale molecular dynamics simulations [29] that the dimers do not interact directly in membrane, with the self-assembly of dimers into rows depending on the membrane deformation caused by individual dimer. Such a view emphasizes the key role of dimers as a pre-requisite for mitochondria morphology and function. Based on such considerations, we are confident that for BN-PAGE analysis Vd/Vm is actually a proper index representing the stability of the overall ATP synthase super-assembly (i.e. the monomer–monomer contacts and the consequent self-assembly of dimers into rows, less stable to detergent extraction and BN-PAGE). A comparison of the Vd/Vm ratios computed for parental and differentiated cells demonstrated a meaningfully higher value for the latter (C: Vd/Vm ratio 0.19 ± 0.02; D: Vd/Vm ratio 0.41 ± 0.06; $p \leq 0.01$; n = 3) (Fig. 1c), suggesting that cardiomyogenesis may favor ATP synthase supra-molecular assembly in our model. Experiments reported in Fig. 1b also indicated a reduced sensitivity of the dimeric protein from D mitochondria to detergent action, which was suggestive of its greater stability.

To qualitatively evaluate protein composition, Vd and Vm forms from both cell types were subjected to classical proteomic analysis. Thus, corresponding gel portions were reduced, alkylated and digested with trypsin under standard conditions, and resulting peptide mixtures were analyzed by nLC–ESI-LIT-MS/MS. Table 1 reports the proteins identified in each ATP synthase band. As result of the poor gel cross-linking properties, various protein components were probably

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t1.1 **Table 1**
t1.2 Qualitative analysis of ATPase subunits in Vm and Vd bands from digitonin-extracted mitochondria of C and D cells. Expasy accession number, protein name and sequence coverage
t1.3 are reported.

t1.4 Accession number	Protein name	Vm C cells coverage (%)	Vm D cells coverage (%)	Vd C cells coverage (%)	Vd D cells coverage (%)
t1.5 P15999	ATP synthase subunit alpha, mitochondrial	51	59	61	67
t1.6 P10719	ATP synthase subunit beta, mitochondrial	63	75	63	67
t1.7 P35435	ATP synthase subunit gamma, mitochondrial	30	31	38	38
t1.8 P35434	ATP synthase subunit delta, mitochondrial	8	14	14	14
t1.9 Q06647	ATP synthase subunit O, mitochondrial	54	64	46	58
t1.10 P19511	ATP synthase subunit b, mitochondrial	41	52	33	41
t1.11 P31399	ATP synthase subunit d, mitochondrial	66	81	78	78
t1.12 P29419	ATP synthase subunit e, mitochondrial	61	70	46	46
t1.13 P11608	ATP synthase protein 8 (A6L)	31	31	34	34
t1.14 Q6PDU7	ATP synthase subunit g, mitochondrial	30	50	30	37

not retained during alkylation/extraction steps, thus determining the improper detection of specific low molecular mass ATP synthase subunits (including IF_1), as already reported in previous studies [55–57].

3.2. Quantitative mass spectrometry analysis of ATP synthase subunits in digitonin-extracted mitochondria

Digitonin-extracted mitochondria from C and D cells were directly analyzed in order to quantify the amount of specific ATP synthase subunits. To this purpose, we applied a targeted proteomic approach based on SRM mass spectrometry and labeled synthetic peptides (AQUA approach), which was previously validated by us for the complex extracted from bovine heart mitochondria [24]. Considering the crucial role documented for the subunit e in mitochondrial ATP synthase supramolecular organization both in yeast [10,22] and mammals [24], and based on the higher value of the dimeric protein observed in D mitochondria (see previous section), we focused on quantification of the amount ratio of the subunit e vs. γ. Subunit γ was used as a reference of known stoichiometry. We selected one representative peptide for each subunit (γ and e) to be quantified, based on the following criteria: i) the peptide has to be unique to the target protein; ii) it has to be devoid of amino acids prone to artifactual modification; iii) it has to show a good MS detectability, based on previous shotgun proteomic data. Thus, peptides VYGTGSLALYEK and YSYLKPR were chosen for subunits γ and e, respectively. Known amounts of corresponding heavy labeled versions ad hoc synthesized were then added to protein extracts from digitonin-treated C and D mitochondria, prior to tryptic digestion. A quantification of the endogenous peptides and their corresponding heavy counterparts was obtained in each sample by using SRM on a triple-quadrupole mass spectrometer [24]. Multiple SRM transitions per peptide were monitored and used for quantification purposes. Signal ratio between the heavy and light peptides was used to calculate the absolute amount of peptides originally present in the samples and, then, the amount ratio of the two proteins. No difference in the ratio was observed between the samples, despite of the increase in the Vd/Vm measured in D mitochondria (Fig. 1c). In fact, the measured ratio (e vs. γ) for C and D was 0.45 ± 0.08 ($n = 3$) and 0.48 ± 0.10 ($n = 4$), respectively. These results indicate a sub-stoichiometric mean value for subunit e in both parental and differentiation-committed cells, and suggest that the higher dimeric protein recovery observed in the latter cannot be ascribed to an enhanced assembly of subunit e.

3.3. Effect of IF_1 on ATP synthase complexes: dimer/oligomer stability and activity regulation

In order to validate BN-PAGE data based on Coomassie blue staining, we further analyzed ATP synthase complexes of digitonin-extracted mitochondria (detergent/protein ratio 3:1 w/w) from D and C cells by 1D-BN-PAGE/immunoblotting experiments using monoclonal antibody anti β subunit. Immunodetection confirmed the presence of Vd in both samples, with the signal being greater in D extracts, and visualized unassembled F_1 in C extracts (Fig. 2a). As result of an augmented sensitivity of this analysis, 1D-BN-PAGE/immunoblotting sometimes revealed just in D extracts two faint bands corresponding to higher oligomeric forms (Fig. S1) This reinforced the hypothesis of an increased stability of the super-assembled complexes in mitochondria of D cells. Nevertheless, higher oligomers were revealed hardly even at low digitonin/protein ratio, whereas when we analyzed bovine heart mitochondria in separate experiments they were well revealed according to high abundance of ATP synthase and elevated stability of the super-assembled complexes (Fig. S1).

Since IF_1 was not detected during proteomic analysis of the bands from BN-PAGE or crude digitonin-extracts, 1D-BN-PAGE/immunoblotting experiments were also performed with monoclonal anti IF_1 antibody. Such method allowed us to probe IF_1 in ATP synthase complexes (Fig. 2b). Unexpectedly, no signal was revealed in Vd of both samples. On the other hand, IF_1 signal was found at the position corresponding to unassembled F_1, even if F_1 band was visualized hardly possibly due to the lower immune-reactivity of antibody anti β with respect to that anti IF_1. This result was in line with the regulatory role of IF_1, which is well known to inhibit the ATP synthase working in reverse, both in vitro and in vivo, thereby counteracting the consequent energy waste [30–32]. Such a role may contribute to avoid futile ATP hydrolysis by the assembly

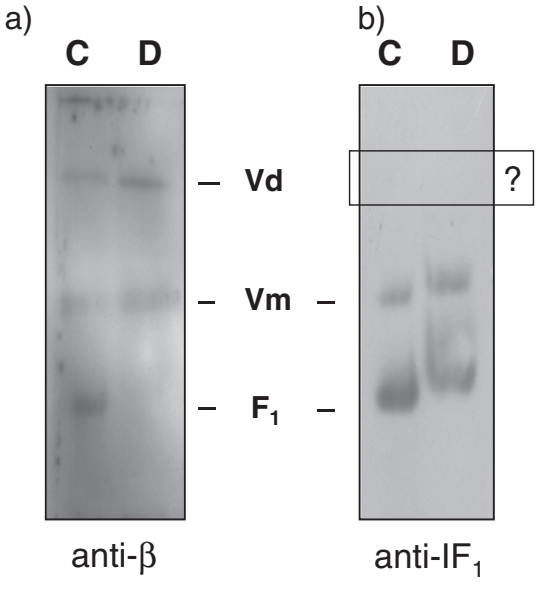

Fig. 2. Immunodetection of IF_1 bound in the ATP synthase complexes resolved in BN-PAGE: the dimer appears to lack IF_1. Control (C) and differentiation-committed (D) mitochondria were solubilized with digitonin using a detergent/proteins ratio 3:1 w/w and subjected to iterative 1D-BN-PAGE/immunoblotting with anti subunit β (a) and IF_1 (b) antibodies. The position of the dimer (Vd), monomer (Vm) and F_1 subcomplex is indicated. The panels show typical results representative of three independent experiments.

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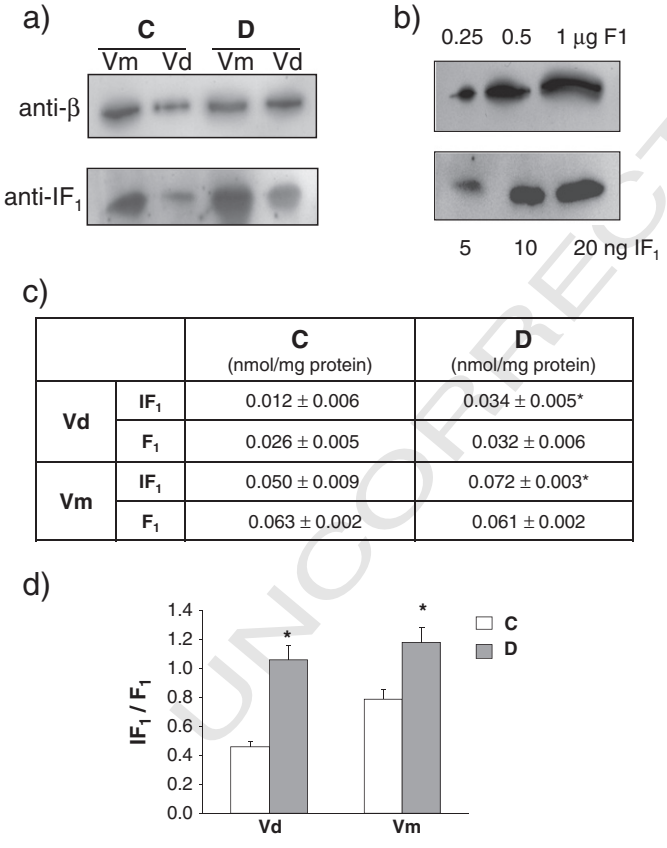
intermediate F_1 in our cells (mainly in C cells), as already suggested for ρ° cells lacking mitochondria-coded subunits [57].

To further investigate on the occurrence of IF_1 in ATP synthase complexes and to evaluate whether its epitope was masked within the dimer, slices of native gel corresponding to Vd and Vm were excised and submitted to 2D SDS-PAGE, followed by immunoblotting with anti β and anti IF_1 antibodies (Fig. 3a). Quantitative levels of these proteins within ATP synthase complexes were then estimated by densitometry based on a calibration with bovine heart IF_1 and F_1 (Fig. 3b). A greater IF_1/F_1 ratio in Vd from mitochondria of D cells was revealed with respect to control (namely, D: 1.06 ± 0.09 vs. C: 0.46 ± 0.02; $p \leq 0.01$, n = 3) (Fig. 3c and d). In accordance, computed IF_1/F_1 ratio in Vm species also suggested a greater amount of bound IF_1 in D cells. In summary, 2D immunoblotting analyses highlighted an increased content of endogenous IF_1 in Vd of mitochondria from cardiac-like differentiating cells, and suggested that IF_1 may contribute to the increased stability of ATP synthase dimer observed in these cells.

To further confirm this phenomenon, additional experiments were performed by using an independent quantitative proteomic approach (see Materials and methods section for details). Thus, Vd and Vm bands from both cell types were washed with 50 mM NH_4HCO_3 and directly subjected to endoprotease LysC digestion. This experimental setup avoided reduced detection of IF_1 resulting from non-proper protein retention in gel knits during reduction/alkylation/extraction steps (see previous section). All gel particles were then extracted and digests analyzed by nLC–ESI-LIT-MS/MS. By extracting and integrating peak areas corresponding to a selected peptide from IF_1, a peptide from subunit γ or two peptides from subunit β in the same nLC–ESI-MS total ion chromatogram, a relative quantitative evaluation of IF_1 in the dimeric and monomeric ATP synthase forms from both cell types was obtained. Independently from the protein used as reference, histograms reported in Fig. 4 confirmed a quantitative trend for IF_1, as resulting from cell differentiation, similar to that reported in Fig. 3. Thus, 2D immunoblotting and MS analyses provided evidence in line with the hypothesis that IF_1 may participate in the enhancement of stability of ATP synthase dimer observed in a physiological range of IF_1 level, in accordance with the results of a recent study performed with human placental mitochondria [34].

Immunodetection of both IF_1 and β subunits was also carried out by 1D SDS-PAGE immunoblotting on mitochondria without separation by BN-PAGE or any other pretreatments. Results of quantitative analysis are shown in Fig. 5a and b. Considering the increased mitochondria mass in the D cells [43], values were referred to citrate synthase activity measured on lysed mitochondria, as a marker of mitochondria mass. Whereas a striking difference was observed in β subunit levels, which were higher in the D cells (in accordance with a greater amount of ATP synthase in the inner membrane), the levels of IF_1 were similar in mitochondria of both C and D cells. This finding indicates that the amount of IF_1, relative to the amount of its target molecule β subunit in F_1 sector, was higher in the parental cells, where conversely it was observed in less quantity as bound in the enzyme (Fig. 3c and d). These results suggest that IF_1 may represent a potential mechanism to provide a more rapid regulatory response in C cells, in line with the recognized regulatory role of IF_1. On the contrary, cardiac-like differentiating cells exhibited a greater steady-state amount of bound IF_1, which was in a molar ratio with F_1 sector close to 1:1 (Fig. 3c and d). Therefore, bound IF_1, contrary to the total levels of IF_1, appeared to augment along with the increase of the levels of β subunit in mitochondria during differentiation, and to parallel with the greater Vd/Vm ratio resolved by BN-PAGE of digitonin-extracts (Figs. 1 and 2), suggesting IF_1 binding as increasing along with F_1F_0-complex biogenesis and super-assembly.

Furthermore, we also investigated whether the different steady-state quantities of IF_1 bound to ATP synthase observed in mitochondria of C and D cells were affecting the enzyme activity. Fig. 5, panel c, shows the ATP synthase and oligomycin-sensitive ATPase maximal activities, measured by two coupled enzyme assays. Also in this case values were referred to citrate synthase activity to normalize the activities vs. mitochondria mass. Oligomycin-sensitive ATPase activity is a measure of the hydrolytic activity of the well coupled F_1F_0-complex, and it does not detect the activity of unassembled F_1 or of IF_1-inhibited F_1F_0-complex. Unexpectedly, markedly higher values were observed in D mitochondria for both ATP synthase and ATPase activities, regardless of the greater quantity of bound IF_1 (Fig. 2). Such increases were previously ascribed by us to the enhanced F_1F_0-complex assembly [43], but in light of the present data this cannot be the only reason, considering the greater quantity of bound IF_1 evocative of a greater inhibitory effect on the ATPase activity. This may suggest a contribution of IF_1-stabilized dimer in favoring a higher enzyme activity. As IF_1 seems not inhibitory but increases the ATP synthesis in cells with IF_1 overexpression [17], and mitochondrial proton motive force is augmented by F_1F_0-ATP synthase oligomerization [14,16], we may infer that the ATP synthase activity was increased in D mitochondria as a result of an increased local proton concentration due to stabilization of F_1F_0 supra-molecular assembly (Fig. 1 and 1-S) and cristae maturation [43]. On the other hand, even ATP hydrolytic activity was increased in D mitochondria, in line with our previous finding that the ATPase activity of dimer separated by BN-PAGE is greater than that of monomer at physiological temperature [18]. We conclude that IF_1-stabilized monomer–



c)

		C (nmol/mg protein)	D (nmol/mg protein)
Vd	IF_1	0.012 ± 0.006	0.034 ± 0.005*
	F_1	0.026 ± 0.005	0.032 ± 0.006
Vm	IF_1	0.050 ± 0.009	0.072 ± 0.003*
	F_1	0.063 ± 0.002	0.061 ± 0.002

Fig. 3. Immunodetection of bound IF_1 in the ATP synthase under denaturing conditions. (a) 2D-SDS-PAGE/immunoblotting analysis of Vd and Vm cut out from BN-PAGE using anti ATP subunit β and anti ATP subunit IF_1 antibodies. (b) Reported quantities of bovine F_1 and IF_1 standards were used for quantification. (c) Mean ratios between the IF_1 subunit amount determined in Vd and Vm and that of the purified bovine IF_1 standard were measured; mean ratios between the β subunit amount determined in Vd and Vm and that of the purified bovine F_1 standard were measured. Values are the mean ± SE of three independent experiments; $p \leq 0.01$ D vs. C. (d) Molar ratios between IF_1 and F_1 in Vm and Vd are reported for control (white bars) and differentiation-committed cells (gray bars). Values are the mean ± SE of three independent experiments; $p \leq 0.01$ D vs. C.

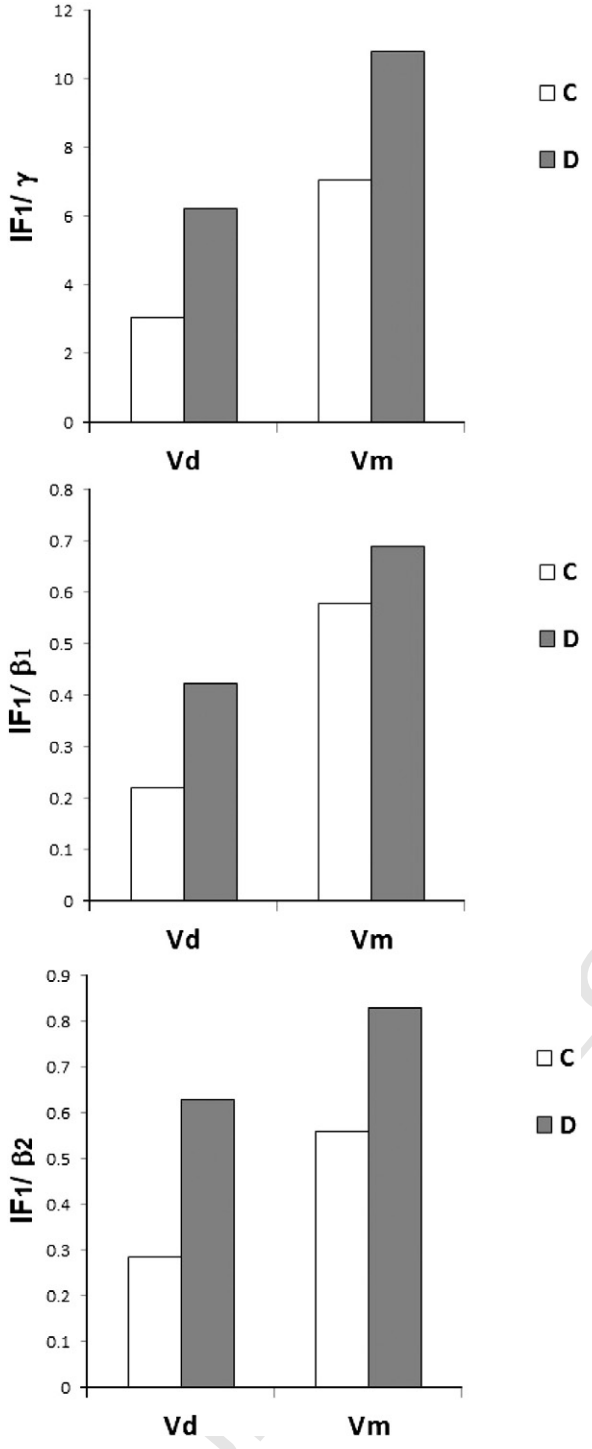
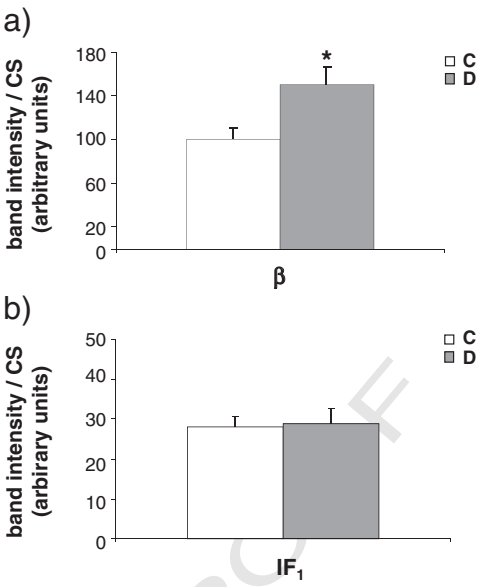


Fig. 4. Relative quantitative MS-based evaluation of IF_1 in monomeric and dimeric ATP synthase in mitochondria from parental and differentiating cells following extraction with digitonin. Experimental details are given in Materials and methods section. Relative quantification of IF_1 was obtained by extracting and integrating peak areas corresponding to peptides TREQLAALK (IF_1), ELIEIISGAAALD (γ), VVDLLAPYAK (β1), and IGLFGGAGVGK (β2) in the same chromatogram. Relative percentage of IF_1 was then obtained by calculating the percentage ratio between peak area of IF_1 peptide and peak areas of γ and/or β peptides.



c)

enzyme activity / CS	C	D
oligomycin–sensitive ATPase	1.83 ± 0.24	3.65 ± 0.34*
ATP synthase	1.25 ± 0.18	2.26 ± 0.28*

Fig. 5. IF_1 and β subunit content in relation with the enzyme activity in mitochondria from parental and differentiating cells. (a, b) Quantitative immunoblot analyses were made for β and IF_1 subunits after 1-D SDS-PAGE of purified mitochondria from parental (C) and differentiation-committed (D) cells. Band intensities based on densitometry were normalized per mg protein and were related to citrate synthase activity. White and gray columns refer to C and D cells, respectively. For both proteins, values are the mean ± SD of four different experiments. *Significantly different with respect to control cells ($p \leq 0.01$). (c) The ATP synthase and the ATPase activities were determined by spectrophotometric assays performed respectively on intact (ATP synthase activity) and on osmotically-shocked (ATPase activity) mitochondria from C and D cells, as reported in Materials and methods. 10 μM oligomycin was used to determine the oligomycin-sensitive ATPase activity, which corresponds to the activity of the correctly assembled F_1F_0-ATP synthase, excluding the activity on unassembled F_1. The activities were normalized to citrate synthase activity. Data represent the mean ± SD of three different experiments. *Significantly different vs. parental control cells ($p \leq 0.01$).

monomer contacts could have provided the enzyme with the ability to sustain a much more efficient ATP hydrolysis with a mechanism which remains to be clarified. In this regard, we advocate the hypothesis that IF_1 may stabilize the dimers as a result of a not-inhibitory binding, which may be in accordance with the recent V-shaped structure of dimer [14,29] with a distance between the two F_1 domains not consistent with the formation of an inhibitory IF_1–IF_1 bridge [33]. The stabilized dimer interface may favor rotor rotation during catalysis. Our finding that dimer bands were activity-stained (Fig. 1) but contained IF_1 in high molar ratio vs. F_1 may be in line with this hypothesis. A not-inhibitory binding anchoring IF_1 in the F_1F_0 complex in membrane was reported on bovine heart submitochondrial particles [58]. Nevertheless, we cannot exclude that, alternatively, ATP hydrolytic activity was IF_1-inhibited for the great fraction of IF_1-stabilized enzyme molecules, and a low fraction of the molecules did not contain IF_1 and was active. If this was the case, the catalytic efficiency of such molecules had to be greatly augmented. In this hypothesis, the overall supra-molecular assembly had to result more stabile and the dimeric structure of the IF_1-free active molecules also maintained.

4. Conclusions

The hypothesis that ATP synthase biogenesis has a crucial role in cardiac-like differentiation of H9c2 has been recently corroborated by BN-PAGE analysis focused on the assembly of F_1F_0-complex and carried out on mitochondria extracted with dodecylmaltoside [43]. Under such conditions, we documented a greater amount of the assembled F_1F_0-enzyme in mitochondrial membrane from cardiac-like

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cells with respect to parental cardiomyoblasts, which conversely showed unassembled F_1 sub-complex in a greater extent. Differentiation was accompanied by mitochondria biogenesis and remodeling in terms of maturation of cristae, which appeared closely packed, and network expansion.

In this study, in order to characterize the super-assembly of ATP synthase, we applied a proteomic approach which was combined with the use of digitonin to solubilize mitochondria and to maintain dimeric/oligomeric complexes, as it is known that the combination of dodecylmaltoside with BN-PAGE dissociates dimeric ATP synthase into the monomeric form. Based on this approach, we may conclude that super-assembly of ATP synthase in mitochondrial membrane is favored during cardiomyogenesis, also suggesting a relationship between the acquisition of greater stability of supra-molecular organization and the mitochondria morphological modifications, i.e. cristae ultrastructure and network expansion. BN-PAGE analysis evaluated the proportion of dimer extracted from mitochondria, thereby demonstrating a higher dimer/monomer ratio in cardiac-like cells than in control, as a measure of a greater stability of the ATP synthase supra-molecular assembly. Quantitative mass spectrometry analysis on subunit e in digitonin-extracted ATP synthase suggested a negligible contribution of this subunit in the improvement observed in ATP synthase supramolecular organization. Interestingly, the sub-stoichiometric mean value found for subunit e in both parental and differentiation-committed cells indicated a similar proportion of complex molecules lacking subunit e in both cases. This is difficult to be explained, due to scarcity of data on the assembly of the accessory subunits, like e subunit, in the process of ATP synthase biogenesis [59]. Nevertheless, it may indicate that the increase in β subunit content occurring during differentiation does not necessarily result in our model in the assembly of enzyme complexes containing all the 15 different subunits [60]. Unfortunately, BN-PAGE was not able to resolve the uncompleted complexes lacking e subunit, in accordance with the small differences expected in their molecular mass values. In conclusion, due to the well known role of subunit e in self-association of ATP synthase [10,22–24], this finding suggests that the super-assembled complexes lacking e subunit were not sufficiently stable for detergent-isolation, consistent with the low amounts of dimer/oligomer observed in digitonin-extracted mitochondria from H9c2 cells. Yet, the acquisition of greater stability of supra-molecular organization occurred in cardiac-like H9c2 had to be likely due to some other factors.

In this regard, we further investigated the controversial role of the mitochondrial inhibitor protein IF_1 in promoting the dimer stability in membrane. We quantified IF_1 by iterative BN-PAGE /2D SDS PAGE and immunoblotting using anti-IF_1 antibody, and confirmed the data by MS/MS quantification of IF_1 in ATP synthase complexes separated by BN-PAGE. We found a more marked amount of IF_1 associated to dimer in cardiac-like differentiating cells, as compared to the parental cells. Together, our present results confirm a role for bound IF_1 in promoting dimer stability and overall supra-molecular assembly, thereby favoring a higher enzyme activity. The hard resolution of higher oligomers on native gel may be explained by the lack of direct dimer–dimer contacts mediated by interstitial proteins [29], which prompt us to believe that the stabilization of monomer–monomer contacts by IF_1 is likely to favor in turn the self-assembly of dimers into rows in membrane, although these are less stable to detergent extraction and native electrophoresis, Such a role for IF_1 is in accordance with data from several independent laboratories [17,33,34,57], but in apparent divergence with others including our previous data [35–37]. These apparently conflicting results may be explained on the basis of the differences in type/abundance of the mitochondrial membranes investigated and/or in the experimental conditions used for solubilization of ATP synthase complexes [27]. In this regard, based on our present data of subunit e quantification, we hypothesize that the stoichiometry of the accessory subunits contributing to enzyme supra-molecular organization, such as subunit e, may play a role in unveiling the IF_1 effect on dimer stability. Indeed, in Triton-extracts of bovine heart mitochondria, which contained both subunit e [24] and IF_1 [18,35] in a molar ratio of ~1 with respect to F_1, we previously found that IF_1 removal did not significantly decrease the dimer content [35]. Conversely, in digitonin extracts of mitochondria from differentiated H9c2 cells, in which ATP synthase contained sub-stoichiometric subunit e but equimolar IF_1 (normalized to F_1), bound IF_1 appeared to improve dimer stability. However, it can't be excluded that the experimental conditions used for solubilization of ATP synthase complexes partially affected the results [27]. Based on these considerations, our present data prompt us to speculate that ATP synthase dimer may be formed even in the absence of IF_1, but the binding of IF_1 plays an important part in dimer stabilization especially if the monomer–monomer contacts through accessory subunits, or F_0 subunits, are partially destabilized. Consistent with this view, a fundamental role of IF_1 in dimer formation was postulated in ρ_0 cells lacking the F_0 subunits a and A6L [57]. However, the way by which IF_1 can stabilize the dimers and favor a higher enzyme activity is far to be elucidated, especially considering the still controversial descriptions of their structures [14,15,28,29].

Of note, our data have been obtained on a normal, non tumor, cell line in a physiological range of IF_1 level, and suggest that the enzyme activation mediated by stabilization of super-assembly via IF_1 binding to dimer may be a physiological response associated to cardiac-like differentiating conditions, which may be of more extensive importance. Indeed, such effects are not conflicting with the opposite effect elicited by IF_1 over-expressed at a very high level, which has been recently shown as resulting in ATP synthesis inhibition and associated to the intriguing mechanisms and signaling pathway by which IF_1 may participate in the biology of cancer cells [61]. It should be emphasized that the actual state of the art of ATP synthase supramolecular organization was reviewed very recently [54], and the need was highlighted to further investigate the possibility that the relationship between cristae morphogenesis and ATP synthase super-assembly is conserved in mammalian cells and is associated with physiological consequences. In our opinion, H9c2 cardiomyoblasts and their counterparts induced to cardiac-like differentiation represent an interesting in vitro model of physiological modulation of cell conditions, where we attempted to characterize ATP synthase super-assembly in relation to cristae morphogenesis.

In conclusion, we demonstrate that IF_1 may provide an important but not exclusive contribution to ATP synthase dimer stability and super-assembly, thereby improving the enzyme catalysis efficiency. Such a contribution is expected to depend on the assembly of the enzyme accessory subunits participating to the supra-molecular organization, and specifically of subunit e which greatly varies with cell types, tissues and physio/pathological conditions [24].

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.bbabio.2013.04.002.

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Conflict of interest

None declared.

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