



ALMA MATER STUDIORUM  
UNIVERSITÀ DI BOLOGNA

## ARCHIVIO ISTITUZIONALE DELLA RICERCA

### Alma Mater Studiorum Università di Bologna Archivio istituzionale della ricerca

The F1Fo-ATPase inhibitor, IF1, is a critical regulator of energy metabolism in cancer cells

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Solaini G., Sgarbi G., Baracca A. (2021). The F1Fo-ATPase inhibitor, IF1, is a critical regulator of energy metabolism in cancer cells. *BIOCHEMICAL SOCIETY TRANSACTIONS*, 49(2), 815-827 [10.1042/BST20200742].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/864674> since: 2022-02-23

*Published:*

DOI: <http://doi.org/10.1042/BST20200742>

*Terms of use:*

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).  
When citing, please refer to the published version.

(Article begins on next page)

# The $F_1F_0$ -ATPase inhibitor, $IF_1$ , is a critical regulator of energy metabolism in cancer cells

Giancarlo Solaini\*, Gianluca Sgarbi, Alessandra Baracca\*

Department of Biomedical and Neuromotor Sciences, Laboratory of Biochemistry and Mitochondrial Pathophysiology, University of Bologna, via Irnerio, 48, 40126 Bologna, Italy

\* Authors to whom correspondence should be addressed: giancarlo.solaini@unibo.it (G.S.); alessandra.baracca@unibo.it (A.B.); Tel.: +39-051-2091215 (G.S.); Tel.: +39-051-2091244 (A.B.)

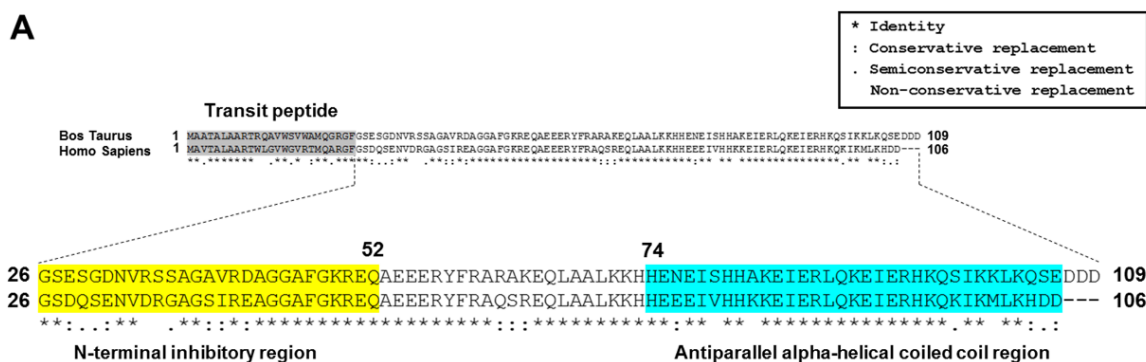
## Abstract

In the last two decades,  $IF_1$ , the endogenous inhibitor of the mitochondrial  $F_1F_0$ -ATPase (ATP synthase) has assumed greater and ever greater interest since it has been found to be overexpressed in many cancers. At present, several findings indicate that  $IF_1$  is capable of playing a central role in cancer cells by promoting metabolic reprogramming, proliferation and resistance to cell death. However, the mechanism(s) at the basis of this pro-oncogenic action of  $IF_1$  remains elusive. Here, we recall the main features of the mechanism of the action of  $IF_1$  when the ATP synthase works in reverse, and discuss the experimental evidence that support its relevance in cancer cells. In particular, a clear pro-oncogenic action of  $IF_1$  is to avoid wasting of ATP when cancer cells are exposed to anoxia or near anoxia conditions, therefore favoring cell survival and tumor growth. However, more recently, various papers have described  $IF_1$  as an inhibitor of the ATP synthase when it is working physiologically (i.e. synthesizing ATP), and therefore reprogramming cell metabolism to aerobic glycolysis. In contrast, other studies excluded  $IF_1$  as an inhibitor of ATP synthase under normoxia, providing the basis for a hot debate. This review focuses on the role of  $IF_1$  as a modulator of the ATP synthase in normoxic cancer cells with the awareness that the knowledge of the molecular action of  $IF_1$  on the ATP synthase is crucial in unravelling the molecular mechanism(s) responsible for the pro-oncogenic role of  $IF_1$  in cancer and in developing related anticancer strategies.

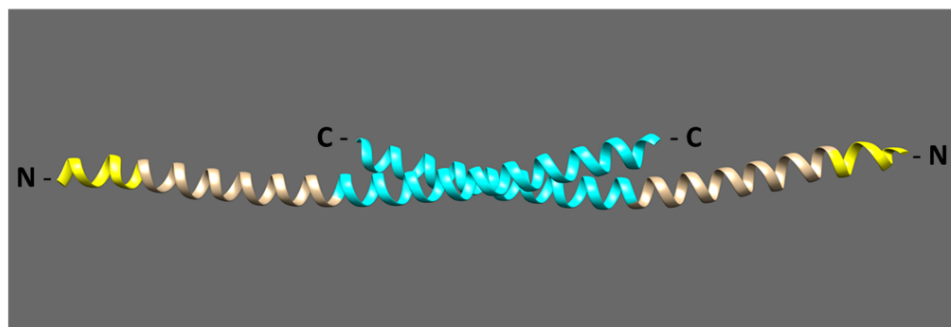
## Introduction

During the last decades, numerous proteins have been shown to express pro-oncogenic action in different cancers. Among these proteins a peculiar and interesting role is played by the endogenous inhibitor of the mitochondrial ATP synthase ( $F_1F_0$ -ATPase),  $IF_1$ , also called “Inhibitor Factor 1”. It is a low molecular mass protein first identified in bovine heart mitochondria by Pullman & Monroy [1] and subsequently it was found ubiquitously expressed in eukaryotes. It has been described in monocellular organisms [2, 3] and more extensively in mammalian tissues, where it was found present at different levels [4-6], and in particular in slow and fast beating hearts animals [7]. The presence of the intrinsic inhibitor and its interaction with the ATP synthase appear of critical importance in eukaryotic cellular life, therefore it is worth clarifying its role(s) also in cancer cells.

The human mature protein, encoded by the nuclear gene *ATP5IF1* in chromosome 1, is composed of 81 amino acids and presents a high sequence homology of about 75% with the bovine  $IF_1$  (Figure 1A). In aqueous solution,  $IF_1$  exists as monomers, dimers, and oligomers depending on the pH. At slightly acidic pH the equilibrium is forced toward the dimeric state (Figure 1B) and the ATP hydrolytic activity of the enzyme is fully inhibited, whereas at alkaline pH  $IF_1$  is predominantly oligomeric and inactive [8, 9]. In addition, the oligomeric state and consequently the inhibitory potency of  $IF_1$  is sensitive to both the ionic strength and the nature of cationic species [8].



**B**



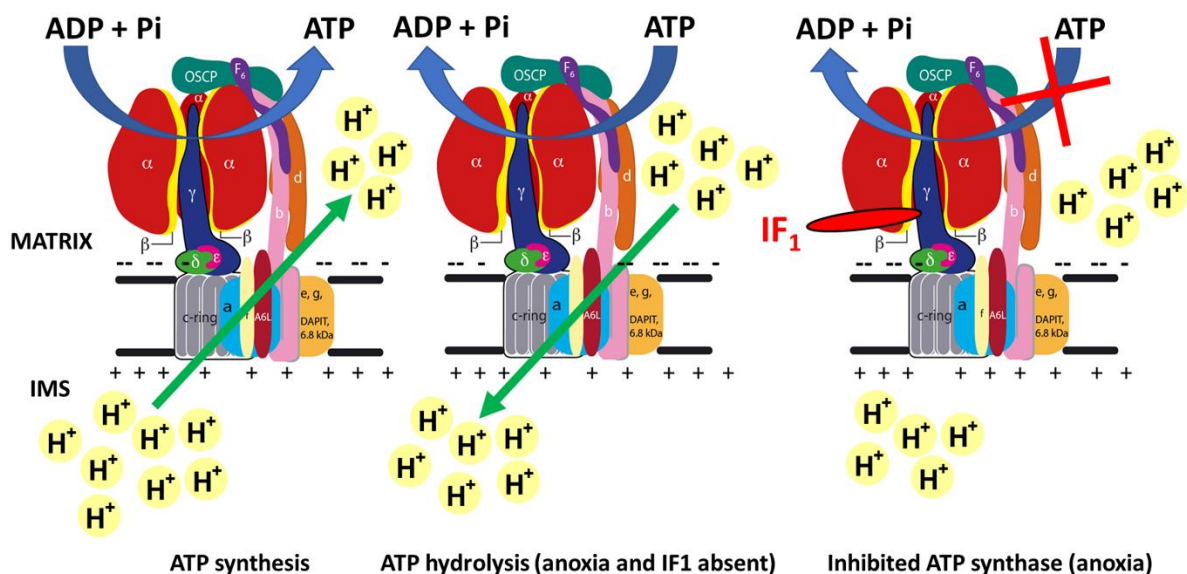
**Figure 1. Protein sequence alignment of bovine and human IF<sub>1</sub> and its dimeric structure.**

(A) Pairwise alignment of the complete sequence of bovine (UniprotKB - P01096) and human (UniprotKB - Q9UII2) IF<sub>1</sub> protein, performed by Clustal omega program. The N-terminal inhibitory and the antiparallel  $\alpha$ -helical coiled coil region are dyed in yellow and cyan, respectively. (B) 3D depiction of the bovine dimeric IF<sub>1</sub> (PDB code: 1GMJ). The representation shows the monomer association via an anti-parallel  $\alpha$ -helical coiled-coil in their C-terminal regions (cyan) and the N-terminal inhibitory regions extending in opposite regions (yellow). The N-terminal domain of both monomers are truncated because only few residues of these domains were resolved in the structure.

In eukaryotes, IF<sub>1</sub> is found in mitochondrial matrix, but it is still unclear whether under physiological conditions it is free or bound to the F<sub>1</sub>F<sub>0</sub>-ATPase. Interestingly, a very recent paper challenged the hypothesized contribution of IF<sub>1</sub> to the formation of inactive ATP synthase tetramers [10]. Nonetheless, the coexistence of active ATP synthase dimers and inactive tetramers, resulting from the binding of IF<sub>1</sub> to ATP synthase dimers in the hydrolytic mode, may be hypothesized considering that individual cristae within the same mitochondrion can have different membrane potentials [11]. Alternatively, under conditions leading to ATP synthase dimers in the hydrolytic mode, tetramers could result from insufficient IF<sub>1</sub> to inhibit all the ATP synthase dimers [10].

At present, IF<sub>1</sub> is considered to be a reversible non-competitive inhibitor of ATP hydrolysis catalyzed by isolated F<sub>1</sub>-ATPase and *in situ* F<sub>1</sub>F<sub>0</sub>-ATPase under conditions of collapsed proton motive force [8] (see scheme, Figure 2). This occurs in the ischemic heart (for review see [12, 13]) and in cancer cells exposed to anoxia or anoxia mimicking uncoupling conditions [14].

The F<sub>1</sub>F<sub>0</sub>-ATPase is a multimeric complex of about 600 kDa mass, located in the inner mitochondrial membrane where it phosphorylates ADP with inorganic phosphate at the expenses of the proton motive force ( $\Delta\mu_{H^+}$ ) produced by the respiratory chain. Its catalytic moiety, F<sub>1</sub>, constituted by 9 subunits,  $\alpha_3\beta_3\gamma\delta\epsilon$  in order of decreased molecular weight, is bound to the membrane sector, F<sub>0</sub>, and protrudes within the matrix. The enzyme complex contains three equivalent catalytic sites located at the  $\alpha$ - $\beta$  interfaces that *in situ* differ one another for the nucleotide affinity. This affinity depends on the interaction of each  $\alpha\beta$  dimer with the  $\gamma$ -subunit. This subunit rotates during the catalytic turnover, therefore on a 360 degrees round, all the three catalytic sites experience the three different affinity states [15]. Notably, the ATP synthase is a reversible enzyme that under collapsed  $\Delta\mu_{H^+}$  hydrolyzes ATP, produced by glycolysis/glycogenolysis in the cytosol of the cells, to contribute re-establishing and maintaining  $\Delta\mu_{H^+}$ . Incidentally, a similar condition occurs *in vivo* on an ischemic tissue. Indeed, the cellular energy metabolism generates acidification of both cytosolic and mitochondrial matrix compartments promoting the formation of the active dimeric state of IF<sub>1</sub> that binds two F<sub>1</sub> molecules, as clearly established by Cabezon et al. [16]. Under collapsed  $\Delta\mu_{H^+}$ , cytosolic ATP can cross the inner mitochondrial membrane in exchange for ADP [17] and the enzyme pumps H<sup>+</sup> from the matrix to the intermembrane space exploiting the energy released by ATP hydrolysis (Figure 2).

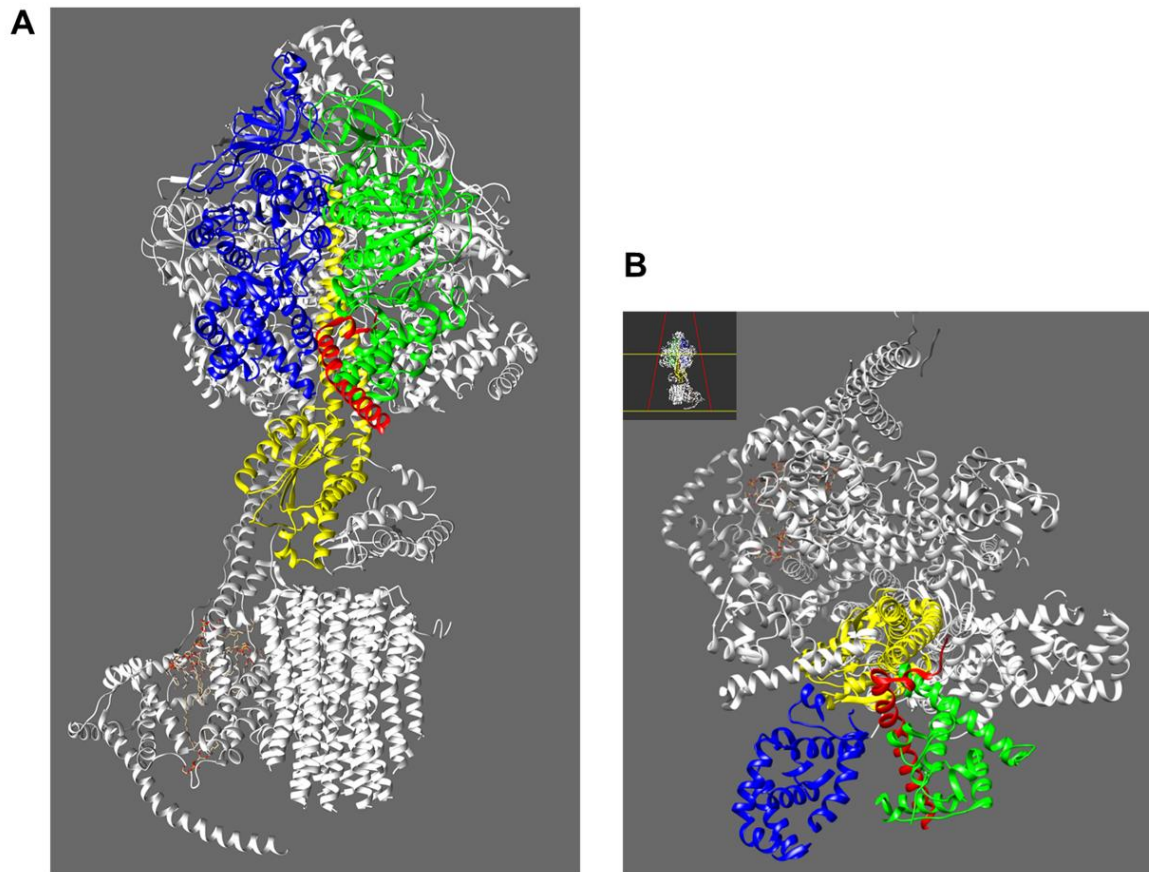


**Figure 2. Schematic presentation of the mitochondrial  $F_1F_0$ -ATPase catalytic activities.**

The Schematic subunit composition of mitochondrial ATP synthase is from Prof. J.E. Walker Medical Research Council, Mitochondrial Biology Unit, University of Cambridge (<http://www.mrc-mbu.cam.ac.uk/projects/2679/subunit-composition>). Left panel: proton transport drives ATP synthesis in cells under physiological condition (normoxia). Central panel refers to  $IF_1$ -silenced cancer cells exposed to anoxia or anoxia-mimicking (uncoupling) conditions. The enzyme pumps protons from the mitochondrial matrix to the IMS (intermembrane space; i.e. intracristae space). The right panel shows the block of the ATPase activity in cancer cells due to the binding of the inhibitor, as it occurs in vivo under anoxia. Green and red arrows indicate allowed and forbidden proton translocation through the ATP synthase, respectively.

The reversal activity of the ATP synthase and the contribution of the ATP/ADP exchange to the transmembrane potential recovery allow mitochondria to save many of their functions, promoting the preservation of cellular homeostasis, and impede the cell death. To this aim, the inhibitory action of  $IF_1$  is fundamental since it allows to maintain the correct balancing between the  $\Delta\mu_{H^+}$  and the ATP levels, avoiding an excessive ATP consumption by the  $F_1F_0$ -ATPase complex [13].

The molecular mechanism of inhibition has been described in detail by Walker and coworkers [18-20]. In synthesis, the same Authors proposed that the inhibitor binds  $F_1$  when it hydrolyzes ATP:  $IF_1$  interacts with the  $\alpha\beta$  dimer at the lowest affinity site for nucleotides (i.e. the empty catalytic site) and following the hydrolysis of two molecules of ATP, it moves into the  $\alpha/\beta$  hexamer preventing the rotor from turning further (Figure 3).



**Figure 3. Binding of IF<sub>1</sub> to the F<sub>1</sub>F<sub>0</sub>-ATPase.** (A) The 3D depiction shows the binding of the N-terminal inhibitory region of IF<sub>1</sub> (red) to the F<sub>1</sub>F<sub>0</sub>-ATPase. The N-terminal region of IF<sub>1</sub> occupies an aqueous cleft between the C-terminal domain of the β<sub>DP</sub> (green) and α<sub>DP</sub> (blue) subunits of the F<sub>1</sub> domain and interacts with the γ subunit (yellow) (PDB code: 7AJF). (B) Upper view of the transversal section of the F<sub>1</sub> domain in close proximity to IF<sub>1</sub> and γ-subunit interaction is shown.

The presence of an endogenous inhibitor of the ATP synthase appears to be of great importance in all the biological systems containing ATP synthases, although its mechanisms of action are still debated, particularly in cancer cells. Several authors from different laboratories reported that IF<sub>1</sub> is overexpressed in human cancer and this has led to the hypothesis about its pro-oncogenic role [see below]. However, in the last two decades, besides the originally described action as an inhibitor of the ATP hydrolytic activity of the enzyme driven by a severe drop of the inner mitochondrial membrane potential ( $\Delta\Psi_m$ ) (i.e. the main component of  $\Delta\mu_{H^+}$ ), several other functions have been ascribed to IF<sub>1</sub> (Table 1).

The present review will describe and discuss two main aspects of proposed roles for IF<sub>1</sub> in cancer. First, the controversial modulation of the ATP synthase activity in cancer cells [5, 21-23] and second, the contribution of IF<sub>1</sub> to modulate reactive oxygen species (ROS) levels and associated protection of cancer cells from apoptosis [23-27].

This will contribute the understanding of the IF<sub>1</sub> functions and the clarification of the molecular mechanisms through which the F<sub>1</sub>F<sub>o</sub>-ATPase is controlled by its endogenous inhibitor. Considering the importance of the ATP synthase, the main producer of energy in human cells to which the whole cell metabolism is strictly associated, understanding the function(s) and defining the molecular mechanism(s) of IF<sub>1</sub> action in cancer cells is essential to open new effective approaches to fight this disease.

**Table 1 Proposed roles for IF<sub>1</sub>**

Action	Mechanism of action	Citation
IF <sub>1</sub> regulates the ATP hydrolysis in hepatoma 22a mitochondria	Almost all F <sub>1</sub> F <sub>o</sub> -ATPase in hepatoma mitochondria have IF <sub>1</sub> bound in a not inhibitory manner, but mitochondria preincubated with an uncoupler decreased the rate of ATP hydrolysis, indicating activation of IF <sub>1</sub>	Chernyak et al. 1991 [28]
IF <sub>1</sub> contributes to the myocardial ischemic preconditioning	IF <sub>1</sub> contributes to the protective mechanism of myocardial preconditioning during the critical phase of the very early reperfusion of the ischemic heart by slowing down the reactivation of the ATP synthase	Bosetti et al. 2000 [29]
IF <sub>1</sub> modulates the activity of angiostatin on the endothelial cell surface	IF <sub>1</sub> binding to surface F <sub>1</sub> F <sub>o</sub> -ATPase conserves ATP particularly at low extracellular pH and it could contribute to modulate angiogenesis	Burwick et al. 2005 [30]
IF <sub>1</sub> promotes dimerization of the mitochondrial F <sub>1</sub> F <sub>o</sub> -ATP synthase	Overexpression of IF <sub>1</sub> in AS-30D hepatoma mitochondria correlated with an increase in the Dimer/Monomer (D/M) ratio of the ATP synthase. Removal of IF <sub>1</sub> increased the F <sub>1</sub> F <sub>o</sub> -ATPase activity and decreased the D/M ratio of the ATP synthase	García et al. 2006 [31]
IF <sub>1</sub> protects the liver from sepsis in rats	It was observed that suppression of IF <sub>1</sub> expression caused elevated mitochondrial F <sub>1</sub> F <sub>o</sub> -ATPase activity, contributing to the bioenergetic failure in the liver during late sepsis	Huang et al. 2007 [32]
IF <sub>1</sub> could play a role in regulating different mitochondrial functions in proximal and distal tubule of nephrons	By measuring the mitochondrial membrane potential and the respiration both in normal conditions and in presence of a specific inhibitor, the Authors hypothesized the role of IF <sub>1</sub> in the regulation of the mitochondrial function of different parts of the kidney tubules	Hall et al. 2009 [33]
Atp1f1 deficiency reduces the synthesis of haem	Atp1f1 regulates the catalytic efficiency of vertebrate ferrochelatase to synthesize haem and its loss may result in congenital sideroblastic anaemias and mitochondriopathies	Shah et al. 2012 [34]
IF <sub>1</sub> limits the apoptotic signalling cascade by preventing mitochondrial remodelling	IF <sub>1</sub> contributes to the structural re-arrangement of mitochondria during apoptosis, modifying the mobilization of Cytochrome c and so altering the downstream cascade of events	Faccenda et al. 2013 [35]
IF <sub>1</sub> as an essential factor for PARK2 recruitment and mitophagy	In uncoupled mitochondria IF <sub>1</sub> promotes collapse of $\Delta\Psi_m$ and activation of the PINK-PARK2 mitophagy pathway by blocking the ATPase activity of the F <sub>1</sub> F <sub>o</sub> -ATP synthase	Lefebvre et al. 2013 [36]
IF <sub>1</sub> plays a role in the glucocorticoids cellular stress-induced program	IF <sub>1</sub> coimmunoprecipitate with the glucocorticoid-induced protein kinase, Sgk-1, at neutral pH, allowing mitochondria to contribute the cellular stress-induced program of the hormones	O'Keeffe et al. 2013 [37]
IF <sub>1</sub> is suggested to promote metabolic preconditioning in neurons	An IF <sub>1</sub> mutant form inhibits the F <sub>1</sub> F <sub>o</sub> -ATPase increasing $\Delta\Psi_m$ and ROS that promotes Akt/p70S6K and PARP repair pathways and Bcl-xL protection from cell death	Formentini et al. 2014 [38]



Reciprocal activation of IF <sub>1</sub> and NF-κB drive Hepatocellular Carcinoma Angiogenesis and Metastasis	IF <sub>1</sub> promoted Snail and vascular endothelial growth factor (VEGF) expression by way of activating nuclear factor kappa B (NF-κB) signaling and IF <sub>1</sub> was directly transcribed by NF-κB, thus forming a positive feedback signaling loop	Song et al. 2014 [39]
Inhibition of ATPIF <sub>1</sub> Ameliorates Severe Mitochondrial Respiratory Chain Dysfunction in Mammalian Cells	A genome-wide genetic screen in haploid human cells revealed that loss of ATPIF <sub>1</sub> strongly protects against antimycin-induced ETC dysfunction and cell death by allowing for the maintenance of mitochondrial membrane potential. The Authors suggested that inhibition of ATPIF <sub>1</sub> can ameliorate severe ETC dysfunction in mitochondrial pathology	Chen et al 2014 [40]
IF <sub>1</sub> is a potential prognostic marker for the migration and invasion of glioma	IF <sub>1</sub> may promote glioma cell migration and invasion through the nuclear factor-κB (NF-κB)/Snail axis since IF <sub>1</sub> knockdown inhibited the expression of NF-κB and Snail, and led to increased E-cadherin expression and reduced vimentin expression.	Wu et al. 2015 [41]
IF <sub>1</sub> mediates the tumor cell cycle	IF <sub>1</sub> knockdown on breast carcinoma cell proliferation suppresses cyclins and cyclin-dependent kinases related to G1/S transition and then induction of G0/G1 arrest	Wei et al. 2015 [42]
IF <sub>1</sub> is a prognostic marker and contributes to proliferation and invasion of human gastric cancer	IF <sub>1</sub> knocked down in gastric cancer cell line SGC-7901 led to a significant reduction of cell proliferation and to the increase of cell death. IF <sub>1</sub> -expressing and -silenced SGC-7901 cells implanted in nude mice confirmed the in vitro results	Yin et al. 2015 [43]
ATPase IF <sub>1</sub> expression is a prognostic factor in non-small cell lung cancer	Elevated expression of IF <sub>1</sub> may be associated with lymph node metastasis of non-small cell lung cancer and serves as an independent prognostic and recurrent indicator for the patients	Gao et al. 2016 [44]
IF <sub>1</sub> contributes the control of mitochondrial remodelling and apoptosis	IF <sub>1</sub> activates a pro-oncogenic mechanism of evasion of apoptosis occurring through optic atrophy 1 (OPA1)-dependent maintenance of cristae shape and preservation of redox balance	Faccenda et al. 2017 [45]
IF <sub>1</sub> seems to contribute the benzopyrene-induced reprogramming of cancer cells to the Warburg effect	The molecular mechanism reported is mainly based on the IF <sub>1</sub> expression increase induced by benzopyrene	Hardonnière et al. 2017 [46]
Role of IF <sub>1</sub> in mitohormesis	The authors hypothesize that the actions of IF <sub>1</sub> on the F <sub>1</sub> F <sub>0</sub> -ATPase are the bases through which the enzyme modulates signaling pathways that allow mitohormesis response (i.e. on ATP, ROS and target of rapamycin)	Esparza-Moltó et al. 2017 [47]
IF <sub>1</sub> sustains migration, invasion and proliferation pancreatic ductal adenocarcinoma cells	IF <sub>1</sub> in both pancreatic acinar cells and pancreatic ductal adenocarcinoma allow to maintain ΔΨ <sub>m</sub> and ATP levels in conditions of chemical hypoxia	Tanton et al. 2018 [48]
Reduction of IF <sub>1</sub> leads to visual impairment in vertebrates	Alterations in IF <sub>1</sub> expression lead to visual impairments in both zebrafish larvae and mice that are associated with an observed interlink between IF <sub>1</sub> level and OPA1 processing	Martín-Jiménez et al. 2018 [49]
IF <sub>1</sub> regulates glucose-stimulated insulin secretion	IF <sub>1</sub> in pancreatic β-cells is bound to the ATP synthase also under normal physiological conditions and its silencing increases insulin secretion over a range of glucose concentrations	Kahancová et al. 2018 [50]
IF <sub>1</sub> inhibition improves the antitumor effect of YC-1 against hepatocellular carcinoma	Limiting the action of IF <sub>1</sub> the p-STAT3 level decreased, determining increased expression of the tumor suppressor gene E-cadherin	Ding et al. 2018 [51]
Overexpression of IF <sub>1</sub> acts as a tumor suppressor in colorectal carcinomas	Overexpression of mitochondrial IF <sub>1</sub> prevents metastatic disease of colorectal cancer by enhancing anoikis and tumor infiltration of natural killer cells	González-Llorente et al. 2019 [52]
IF <sub>1</sub> contributes the control of Ca <sup>2+</sup> homeostasis	IF <sub>1</sub> is required for maintaining mitochondrial Ca <sup>2+</sup> homeostasis by regulating the expression of the Ca <sup>2+</sup> uniporter (MCU) via the AMPK/CREB pathway	Faccenda et al. 2021 [53]



## **IF<sub>1</sub> is overexpressed in human cancer**

The first evidence of overexpressed IF<sub>1</sub> in mammalian cancer was provided by Luciakova and Kuzela [54] who observed that the content of F<sub>1</sub>-ATPase in mitochondria of Zajdela hepatoma and Yoshida sarcoma did not differ significantly from that measured in mitochondria of rat liver and heart, whereas the content of IF<sub>1</sub> revealed that the tumor mitochondria contained 2-3-times more ATPase inhibitor than rat liver and heart. Subsequently, Capuano et al. [55] analyzing the oxidative phosphorylation enzymes in human normal and neoplastic cells confirmed the higher level of IF<sub>1</sub> compared to that of the F<sub>1</sub>F<sub>o</sub>-ATPase. In a more recent paper, Bravo et al. [56] agreed with previous studies and reported a 2-fold enhancement of IF<sub>1</sub> content in hepatoma AS-30D submitochondrial particles compared to normal rat liver controls. Finally, Cuezva et al. [5, 25, 26] reported IF<sub>1</sub> to F<sub>1</sub>F<sub>o</sub>-ATPase ratios greater than two in different types of human and cancer cells. High levels of IF<sub>1</sub> in a number of cancers have been linked to increased glycolysis, resistance to cell death, increased migration, and proliferation [39]. These connections and the need to define the role of this overexpressed protein in many cancers pushed a number of researchers to deeper investigate the function(s) and the mechanism(s) of action of IF<sub>1</sub> in cancer cells. Only with a clear-cut identification of the molecular mechanisms of action of a pro-oncogenic factor as IF<sub>1</sub>, will the scientific basis be established for drug development to oppose proliferation and diffusion of cancer cells, and resistance to the action of drugs.

## **IF<sub>1</sub> and metabolic reprogramming in cancer cells**

Cancer cell metabolism is extremely heterogeneous and it might promptly change to adapt and suitably interact with the microenvironment. The heterogeneity of the metabolism, the capability to interact with different microenvironments, and the great proliferation rate characterizing cancer cells require reprogramming their metabolism compared to parental, non-transformed cells. Alterations of cellular metabolism are considered crucial hallmarks of cancer and are essentially determined by mutational events that combine altering multiple and fundamental signalling pathways [57-60]. Here, the energetic metabolism of cancer cells, in particular the modulation of the activity of mitochondrial F<sub>1</sub>F<sub>o</sub>-ATPase, that can be affected by IF<sub>1</sub>, will be addressed.

It is well known that many cancer cells adopt the so-called aerobic glycolysis, “Warburg effect” [61], consisting in a higher glycolytic flux (2-17 fold) compared to normal cells in the presence of physiological concentrations of oxygen [62]. Aerobic glycolysis is certainly induced by oncogenes such as MYC and the hypoxia inducible factor HIF-1 that increase the level of glycolytic enzymes and inhibit pyruvate oxidation, therefore limiting the rate of the tricarboxylic acid cycle and the coupled rate of oxidative phosphorylation

(OXPHOS) [63, 64]. This allows cancer cells to meet both the great requirement of glycolytic intermediates to produce mass, reducing equivalents (NADPH), and supply ATP to support the high anabolism necessary for the great proliferation rate of cancer cells [65, 66]. According to the above evidence and considering the tight control of ADP phosphorylation by the mitochondrial membrane potential,  $\Delta\Psi_m$ , one might assume that IF<sub>1</sub> does not play any significant role in mediating the shift of cancer cells to an enhanced aerobic glycolysis. Nonetheless, in several papers, proposing the involvement of IF<sub>1</sub> in the modulation of ATP synthesis is proposed. Indeed, over the past decade Cuezva and coworkers reported that IF<sub>1</sub> is as an important player in cancer cell acquisition of the Warburg metabolic phenotype [5, 26, 67]. The first of these studies was based on assays carried out in mouse hepatoma (Hepa 1–6), human hepatocarcinoma (HepG2), and cervix carcinoma (HeLa) cells in which IF<sub>1</sub> was transiently overexpressed or silenced [5]. The authors observed that overexpression of IF<sub>1</sub> in cells expressing low levels of IF<sub>1</sub> triggered the upregulation of aerobic glycolysis and the inhibition of state 3 respiration rate (ADP-stimulated respiration rate) with concurrent mitochondrial hyperpolarization. In addition, the authors observed that IF<sub>1</sub> overexpression mimicked the effects of cell treatment with the ATP synthase inhibitor oligomycin, and from this observation drew the conclusion that IF<sub>1</sub> controls the activity of oxidative phosphorylation by inhibiting the F<sub>1</sub>F<sub>o</sub>-ATPase under the physiological conditions of ATP synthesis. Subsequently, the same authors reported similar findings with human colon tumor cells (HCT116) [25]. Recently, Kahancova et al. [50] inferred that IF<sub>1</sub> inhibits the ATP synthesis rate in a model of pancreatic  $\beta$ -cells. Their hypothesis was based on the observation that both ATP concentration and state 3 respiration decreased in cells overexpressing IF<sub>1</sub>, and that IF<sub>1</sub> silencing resulted in the opposite effect. However, in neither set of experiment was the synthetic or hydrolytic activity of the F<sub>1</sub>F<sub>o</sub>-ATP synthase determined directly *in situ*, although it would have been crucial to do so. In addition, both overexpression and silencing of IF<sub>1</sub> were transient, and therefore the cellular content of IF<sub>1</sub> cell content was heterogeneous and cells experienced an unstable condition that is far from an unperturbed steady-state.

Conversely, other researchers, working independently, reported that IF<sub>1</sub> inhibited the ATP synthase complex only when it works in reverse, hydrolyzing ATP, a condition widely described in the earliest literature as above mentioned. Indeed, Campanella et al. [22] in HL-1, C2C12, and HeLa cells observed that IF<sub>1</sub> overexpression increased the formation of dimeric ATP synthase complexes that was associated with an increased F<sub>1</sub>F<sub>o</sub>-ATP synthase activity. Although the authors approached the study by means of an indirect method based on the assay of  $\Delta\Psi_m$  in cells containing or lacking IF<sub>1</sub>, under conditions of fully active or oligomycin-inhibited oxidative phosphorylation, the decrease in  $\Delta\Psi_m$  induced by IF<sub>1</sub> was confirmed subsequently by others [14, 21, 23, 48, 68] directly measuring the ATP synthesis rate using reliable luminometric assays. The presence of IF<sub>1</sub> never caused an inhibition of the ATP synthesis rate by OXPHOS in different cancer cell lines. In addition, Sgarbi et al. [14] showed that

also in severe hypoxia (up to 0.1% O<sub>2</sub>) osteosarcoma 143B cells synthesized ATP, although at a lower rate compared to normoxic conditions, but the rate was unchanged whether IF<sub>1</sub> was expressed or silenced. These results were in line with the  $\Delta\Psi_m$  measurements carried out in IF<sub>1</sub>-expressing and -silenced cells and crucially,  $\Delta\Psi_m$  values were unaffected by the addition of oligomycin, thus excluding any contribution to  $\Delta\Psi_m$  from ATP hydrolysis. Under anoxia-mimicking conditions (uncoupling conditions) the presence of IF<sub>1</sub> allowed the  $\Delta\Psi_m$  collapse, whilst in IF<sub>1</sub>-silenced cells it was significantly preserved at the expenses of glycolytic ATP [27]. It should be stressed, that in osteosarcoma cells the expression of IF<sub>1</sub> was sufficient to inhibit the entire ATPase activity, as shown by measuring the ATP level of oligomycin-inhibited and control cells exposed to an uncoupler [14]. Similar experiments were performed also using a stably IF<sub>1</sub>-silenced human embryonic kidney cell lines (HEK-293), and they fully confirmed the results obtained in the osteosarcoma experiments. IF<sub>1</sub>-induced  $\Delta\Psi_m$  collapse matched results obtained under uncoupling conditions in HeLa cells [36]. Finally, ATP hydrolysis by ATP synthase reconstituted into phospholipid vesicles was, as expected, inhibited by IF<sub>1</sub>, and ATP synthesis could only be observed in the presence of IF<sub>1</sub> to inhibit low levels of uncoupled enzyme in the vesicles, which otherwise would destroy any newly synthesized ATP [68]. The clear conclusion from the above investigations is that IF<sub>1</sub> is excluded from contributing to the metabolic reprogramming of cancer cells towards a Warburg effect under normal and even in hypoxic conditions.

Besides the above experimental results, the inhibition of the ATP synthase by IF<sub>1</sub> under physiological conditions could be excluded in principles. As described briefly in the Introduction section, the molecular mechanism of the IF<sub>1</sub> mediated-ATP hydrolytic inhibition has been exhaustively clarified [18]. As all recognize, the ATP synthase complex is a reversible enzyme: it can catalyze both the synthesis of ATP driven by proton translocation from the IMS to the matrix and the reverse reaction pumping protons towards the IMS driven by ATP hydrolysis. Clearly, the direct and the reverse reaction proceed through mirror mechanisms. IF<sub>1</sub> cannot inhibit the synthesis of ATP by the same mechanism adopted to block ATP hydrolysis. Indeed, as widely demonstrated, conditions leading to ATP synthesis (i.e. proton motive force onset and returning to matrix pH physiological value) promoted IF<sub>1</sub> release from the enzyme, as occurs in reperfusion following an ischemic insult [4, 29, 69, 70]. Therefore, the proposed role of IF<sub>1</sub> as inhibitor of ATP synthesis by OXPHOS lacks a clear-cut molecular mechanism.

Finally, some years ago, it was reported that IF<sub>1</sub> in mitochondria can be phosphorylated and dephosphorylated at residue Ser-14 and that the only dephosphorylated protein binds to and inhibits the mitochondrial ATP synthase [67]. This observation could be of considerable scientific and translational interest. However, it is noteworthy that Ser-14 is not an absolutely conserved residue in mammalian IF<sub>1</sub> proteins, and therefore this proposed mechanism of regulation requires further investigation.

## **IF<sub>1</sub> modulates reactive oxygen species in cancer cells**

Another important and undefined aspect of the overexpression of IF<sub>1</sub> in cancer cells concerns its possible role in homeostasis of reactive oxygen species (ROS) homeostasis, given the roles of ROS in cancer pathogenesis and expansion. Low levels of ROS are modulators at transcriptional sites and support cancer development and progression [71, 72]. Elevated levels of ROS have been observed generally in cancer cells, and increased levels of mitochondrial ROS were shown to promote cell proliferation, survival, and migration [73-75]. For these reasons the targeting of mitochondria to the disruption of cell redox communication might be considered to be promising for the development of an anticancer strategy [76]. Indeed, high levels of ROS are toxic to cells [75] and the induction of their elevation by therapeutic intervention could represent a valid approach to cancer therapy, as supported by various studies [77-79]. Therefore, ROS might be considered to be a double-edged sword in cancer. This section will be focused mainly on the association between IF<sub>1</sub>, the levels of ROS, and resistance to cell death in cancer cells.

Campanella et al. [24] analyzed and compared the rate of oxidation of dihydroethidium (DHE) in HeLa cells with IF<sub>1</sub> either transiently overexpressed (+IF<sub>1</sub>) or silenced (-IF<sub>1</sub>) in order to evaluate the respective ROS level and to assess the possible role of IF<sub>1</sub> in regulating autophagy. The experiments showed that the expression of IF<sub>1</sub> played a significant role in defining both resting rates of ROS generation and cellular content of mitochondria, allowing the conclusion to be drawn that IF<sub>1</sub> diminished mitochondrial ROS generation, limiting autophagy which was significantly increased by knockdown of IF<sub>1</sub>. The action of IF<sub>1</sub> as a decreasing factor of ROS level in cells found a strong corroboration by the work of Fujikawa et al. [23] who showed that the ROS level HeLa cells where IF<sub>1</sub> had been knocked down stably was double the level in controls, and associated this to the higher  $\Delta\Psi_m$  measured in IF<sub>1</sub> knockdown cells. However, it is noteworthy that although ROS levels increased in IF<sub>1</sub> knockdown HeLa cells, their growth was unaffected. Similar results were obtained in osteosarcoma 143B cells in our laboratory [21]. Further support to the assertion that IF<sub>1</sub> is capable to limiting ROS levels in cancer cells came from a comparison of ROS levels in osteosarcoma cells grown under normoxic and severe hypoxic conditions (0.5% O<sub>2</sub>) [27]. By means of the CellROX fluorescent probe which senses peroxides and other oxidants, total ROS were assayed in osteosarcoma 143B cells containing IF<sub>1</sub> and in the same cells where IF<sub>1</sub> had been stably silenced. Under both normoxic and hypoxic conditions the presence of IF<sub>1</sub> clearly correlated with a significantly lower level of ROS than in its absence. Concurrently, this work also showed that in osteosarcoma IF<sub>1</sub>-silenced cells, the superoxide level in mitochondria as measured with the MitoSOX Red probe, was higher than that in cells where IF<sub>1</sub> was being expressed. Interestingly, the level of ROS in hypoxic osteosarcoma cells has decreased significantly compared to the normoxic conditions whether or

not IF<sub>1</sub> was expressed. These findings are consistent with previously reported results obtained by analyzing the O<sub>2</sub> tension-dependence of ROS levels in human fibroblasts [80].

However, a number of papers reported dissimilar results, where in contrast, the levels of ROS were enhanced by increases in the levels of IF<sub>1</sub>. Thus, Formentini et al. [25] observed that upregulation of IF<sub>1</sub> in HCT116 cells triggered a significant increase in the production of superoxide, as evaluated by the MitoSOX probe and that a pretreatment with the mitochondrial antioxidant MitoQ [81] quenched superoxide production in IF<sub>1</sub> overexpressing cells, and also ameliorated the basal level of mitochondrial ROS in control cells. The authors also reported that overexpression of IF<sub>1</sub> did not affect the levels of cellular hydrogen peroxide or the GSH/GSSG ratio. The latter observations seem quite in contrast due to the well-known action of the superoxide dismutases, which are ubiquitously present in human cells, to convert the superoxide radicals into hydrogen peroxide with high rate and efficiency [82]. On the basis of their findings, the authors proposed the following sequence of events: IF<sub>1</sub> overexpression → upregulation of the level of ROS (o superoxide) → promotion of NF-κB transcriptional activation via IκBα downregulation and phosphorylation → increase rate of proliferation, invasiveness and Bcl-xL-mediated resistance to drug-induced apoptosis. The role of IF<sub>1</sub> in conferring resistance to staurosporin-induced apoptosis was supported by experimental evidence carried out in different types of cancer cells [25, 26, 45]. However, according to Faccenda et al. [45] it occurred independently from activation of the NF-κB pathway. Indeed, dimeric IF<sub>1</sub> could stabilize the oligomerization of the ATP synthase binding between two monomeric ATP synthases in two adjacent dimers [10]. This might prevent OMA1-induced OPA1 processing that impedes mitochondrial cristae re-modelling [45, 53], thus inhibiting cytochrome c release and the activation of the intrinsic apoptotic pathway. OMA1 is a mitochondrial inner membrane metallopeptidase and its activation may be promoted by various stress cellular signals as low cellular ATP level, altered  $\Delta\Psi_m$  and increased oxidative stress [83]. As supported by experimental data, in addition to its direct role in mitochondria morphology and cristae shaping, IF<sub>1</sub> could counteract apoptosis and confer chemoresistance to cancer cells by preserving ATP level that in turn contributes to the maintenance of an efficient antioxidant defense system (i.e. GSH and peroxiredoxins) and low cellular level of ROS [45]. To conclude, we should point out that in cancer cells the link between ROS and IF<sub>1</sub> will be revealed only when the action of IF<sub>1</sub> on the ATP synthase has been established definitively.

## **Concluding remarks**

Three main points are clear-cut and generally agreed upon by the scientific community concerning the role of IF<sub>1</sub> in cancer cells: first, IF<sub>1</sub> is overexpressed in many cancer cells; second, IF<sub>1</sub> displays a pro-oncogenic potential; and third, IF<sub>1</sub> inhibits the ATP hydrolytic activity of the mitochondrial F<sub>1</sub>F<sub>0</sub>-ATPase

under conditions of collapsed  $\Delta\mu_{H^+}$  in cells, such as occurs under conditions of severe  $O_2$  deficiency such as is found in solid tumors, where oxygen deficiency occurs. In addition, other molecular mechanisms have been advanced to explain the pro-oncogenic activity of  $IF_1$ , but until now, the experimental findings are contradictory and certainly insufficient. In particular, the proposed role of  $IF_1$  in metabolic reprogramming of cancer cells under the condition of  $F_1F_0$ -ATPase synthesizing ATP requires further experimental validation, as this facet is advanced as a molecular explanation for the role of  $IF_1$  in tumorigenesis. An understanding of the biological roles and mechanism(s) of the interaction of  $IF_1$  with the ATP synthase is crucial for developing valuable diagnostic and therapeutic targets for cancer and possibly other human diseases.

## **Perspectives**

- (i) Defining the molecular mechanism(s) of the pro-oncogenic action of  $IF_1$ , the main regulator of mitochondrial ATP synthase, is essential if the protein is to be developed as a target for cancer therapy.
- (ii) Our current knowledge of the molecular action of  $IF_1$  is that it acts to prevent ATP hydrolysis by the ATP synthase working in reverse (for example during anoxia). In dispute is the role of  $IF_1$  in normoxic cancer cells since it has been proposed that  $IF_1$  also inhibits the ATP synthase activity. Accordingly, divergent modulation of intracellular ROS homeostasis has been reported.
- (iii) Future reproducible experiments are required to resolve the currently opposed views concerning the action of  $IF_1$  in normoxic cancer cells. These experiments should also identify both the site of binding of  $IF_1$  to the enzyme and its molecular mechanism of action.

### **Author Contributions:**

G.S. (Giancarlo Solaini) and A.B. (Alessandra Baracca) wrote the manuscript; All authors (G.S. A.B. and G.Sg., Gianluca Sgarbi) contributed to the discussion, writing, review and editing the manuscript.

### **Declaration of Interests:**

The authors declare no conflict of interest.

### **Acknowledgements:**

We apologize to all colleagues whose work could not be cited due to space constraints

## Funding:

We acknowledge funding support by Fondazione Cassa di Risparmio in Bologna, Italy; project n. 358 “Modulation of tumor metabolism associated with IF<sub>1</sub> silencing as new therapeutic strategy” (2018) for economical support.

## Bibliography

- 1 Pullman, M.E., Monroy, G.C. (1963) A naturally occurring inhibitor of mitochondrial adenosine triphosphatase. *J Biol Chem* **238**, 3762-3769.
- 2 Ichikawa, N., Yoshida, Y., Hashimoto, T., Tagawa, K. (1996) An intrinsic atpase inhibitor binds near the active site of yeast mitochondrial F<sub>1</sub>-ATPase. *J Biochem* **119**, 193-199 <https://doi.org/10.1093/oxfordjournals.jbchem.a021208>.
- 3 Satre, M., de Jerphanion, M.B., Huet, J., Vignais, P.V. (1975) ATPase inhibitor from yeast mitochondria. Purification and properties. *Biochim Biophys Acta* **387**, 241-255 [https://doi.org/10.1016/0005-2728\(75\)90107-3](https://doi.org/10.1016/0005-2728(75)90107-3).
- 4 Rouslin, W. (1987) Factors affecting the reactivation of the oligomycin-sensitive adenosine 5'-triphosphatase and the release of ATPase inhibitor protein during the re-energization of intact mitochondria from ischemic cardiac muscle. *J Biol Chem* **262**, 3472-3476.
- 5 Sánchez-Cenizo, L., Formentini, L., Aldea, M., Ortega, A.D., García-Huerta, P., Sánchez-Aragó, M., et al. (2010) Up-regulation of the ATPase inhibitory factor 1 (IF<sub>1</sub>) of the mitochondrial H<sup>+</sup>-ATP synthase in human tumors mediates the metabolic shift of cancer cells to a Warburg phenotype. *J Biol Chem* **285**, 25308-25313 <https://doi.org/10.1074/jbc.M110.146480>.
- 6 Yamada, E.W., Huzel, N.J. (1992) Distribution of the ATPase inhibitor proteins of mitochondria in mammalian tissues including fibroblasts from a patient with Luft's disease. *Biochim Biophys Acta* **1139**, 143-147 [https://doi.org/10.1016/0925-4439\(92\)90093-3](https://doi.org/10.1016/0925-4439(92)90093-3).
- 7 Rouslin, W. (1987) The mitochondrial adenosine 5'-triphosphatase in slow and fast heart rate hearts. *Am J Physiol* **252**, H622-627 <https://doi.org/10.1152/ajpheart.1987.252.3.H622>.
- 8 Boreikaite, V., Wicky, B.I.M., Watt, I.N., Clarke, J., Walker, J.E. (2019) Extrinsic conditions influence the self-association and structure of IF<sub>1</sub>, the regulatory protein of mitochondrial ATP synthase. **116**, 10354-10359 <https://doi.org/10.1073/pnas.1903535116>.
- 9 Cabezón, E., Butler, P.J., Runswick, M.J., Walker, J.E. (2000) Modulation of the oligomerization state of the bovine F<sub>1</sub>-ATPase inhibitor protein, IF<sub>1</sub>, by pH. *J Biol Chem* **275**, 25460-25464 <https://doi.org/10.1074/jbc.M003859200>.
- 10 Spikes, T.E., Montgomery, M.G., Walker, J.E. (2021) Interface mobility between monomers in dimeric bovine ATP synthase participates in the ultrastructure of inner mitochondrial membranes. **118**, <https://doi.org/10.1073/pnas.2021012118>.
- 11 Wolf, D.M., Segawa, M., Kondadi, A.K., Anand, R., Bailey, S.T. (2019) Individual cristae within the same mitochondrion display different membrane potentials and are functionally independent. **38**, e101056 <https://doi.org/10.15252/embj.2018101056>.
- 12 Green, D.W., Grover, G.J. (2000) The IF<sub>1</sub> inhibitor protein of the mitochondrial F<sub>1</sub>F<sub>0</sub>-ATPase. *Biochim Biophys Acta* **1458**, 343-355 [https://doi.org/10.1016/s0005-2728\(00\)00085-2](https://doi.org/10.1016/s0005-2728(00)00085-2).
- 13 Solaini, G., Harris, D.A. (2005) Biochemical dysfunction in heart mitochondria exposed to ischaemia and reperfusion. *Biochem J* **390**, 377-394 <https://doi.org/10.1042/bj20042006>.
- 14 Sgarbi, G., Barbato, S., Costanzini, A., Solaini, G., Baracca, A. (2018) The role of the ATPase inhibitor factor 1 (IF<sub>1</sub>) in cancer cells adaptation to hypoxia and anoxia. *Biochim Biophys Acta Bioenerg* **1859**, 99-109 <https://doi.org/10.1016/j.bbabi.2017.10.007>.
- 15 Boyer, P.D. (1997) The ATP synthase--a splendid molecular machine. *Annu Rev Biochem* **66**, 717-749 <https://doi.org/10.1146/annurev.biochem.66.1.717>.
- 16 Cabezón, E., Montgomery, M.G., Leslie, A.G., Walker, J.E. (2003) The structure of bovine F<sub>1</sub>-ATPase in complex with its regulatory protein IF<sub>1</sub>. *Nat Struct Biol* **10**, 744-750 <https://doi.org/10.1038/nsb966>.



- 17 Maldonado, E.N., DeHart, D.N., Patnaik, J. (2016) ATP/ADP turnover and import of glycolytic ATP into mitochondria in cancer cells is independent of the adenine nucleotide translocator. **291**, 19642-19650 <https://doi.org/10.1074/jbc.M116.734814>.
- 18 Bason, J.V., Montgomery, M.G., Leslie, A.G., Walker, J.E. (2014) Pathway of binding of the intrinsically disordered mitochondrial inhibitor protein to  $F_1$ -ATPase. *Proc Natl Acad Sci U S A* **111**, 11305-11310 <https://doi.org/10.1073/pnas.1411560111>.
- 19 Bason, J.V., Runswick, M.J., Fearnley, I.M., Walker, J.E. (2011) Binding of the inhibitor protein  $IF_1$  to bovine  $F_1$ -ATPase. *J Mol Biol* **406**, 443-453 <https://doi.org/10.1016/j.jmb.2010.12.025>.
- 20 Gledhill, J.R., Montgomery, M.G., Leslie, A.G., Walker, J.E. (2007) How the regulatory protein,  $IF_1$ , inhibits  $F_1$ -ATPase from bovine mitochondria. *Proc Natl Acad Sci U S A* **104**, 15671-15676 <https://doi.org/10.1073/pnas.0707326104>.
- 21 Barbato, S., Sgarbi, G., Gorini, G., Baracca, A., Solaini, G. (2015) The inhibitor protein ( $IF_1$ ) of the  $F_1F_0$ -ATPase modulates human osteosarcoma cell bioenergetics. *J Biol Chem* **290**, 6338-6348 <https://doi.org/10.1074/jbc.M114.631788>.
- 22 Campanella, M., Casswell, E., Chong, S., Farah, Z., Wieckowski, M.R., Abramov, A.Y., et al. (2008) Regulation of mitochondrial structure and function by the  $F_1F_0$ -ATPase inhibitor protein,  $IF_1$ . *Cell Metab* **8**, 13-25 <https://doi.org/10.1016/j.cmet.2008.06.001>.
- 23 Fujikawa, M., Imamura, H., Nakamura, J., Yoshida, M. (2012) Assessing actual contribution of  $IF_1$ , inhibitor of mitochondrial  $F_0F_1$ , to ATP homeostasis, cell growth, mitochondrial morphology, and cell viability. *J Biol Chem* **287**, 18781-18787 <https://doi.org/10.1074/jbc.M112.345793>.
- 24 Campanella, M., Seraphim, A., Abeti, R., Casswell, E., Echave, P., Duchon, M.R. (2009)  $IF_1$ , the endogenous regulator of the  $F_1F_0$ -ATP synthase, defines mitochondrial volume fraction in HeLa cells by regulating autophagy. *Biochim Biophys Acta* **1787**, 393-401 <https://doi.org/10.1016/j.bbabi.2009.02.023>.
- 25 Formentini, L., Sánchez-Aragó, M., Sánchez-Cenizo, L., Cuezva, J.M. (2012) The mitochondrial ATPase inhibitory factor 1 triggers a ROS-mediated retrograde prosurvival and proliferative response. *Mol Cell* **45**, 731-742 <https://doi.org/10.1016/j.molcel.2012.01.008>.
- 26 Sánchez-Aragó, M., Formentini, L., Martínez-Reyes, I., García-Bermudez, J., Santacatterina, F., Sánchez-Cenizo, L., et al. (2013) Expression, regulation and clinical relevance of the ATPase inhibitory factor 1 in human cancers. *Oncogenesis* **2**, e46 <https://doi.org/10.1038/oncsis.2013.9>.
- 27 Sgarbi, G., Gorini, G., Liuzzi, F., Solaini, G., Baracca, A. (2018) Hypoxia and  $IF_1$  expression promote ROS decrease in cancer cells. *Cells* **7**, <https://doi.org/10.3390/cells7070064>.
- 28 Chernyak, B.V., Dukhovich, V.F., Khodjaev, E. (1991) Regulation of ATP hydrolysis in hepatoma 22a mitochondria. *Arch Biochem Biophys* **286**, 604-609 [https://doi.org/10.1016/0003-9861\(91\)90087-y](https://doi.org/10.1016/0003-9861(91)90087-y).
- 29 Bosetti, F., Yu, G., Zucchi, R., Ronca-Testoni, S., Solaini, G. (2000) Myocardial ischemic preconditioning and mitochondrial  $F_1F_0$ -ATPase activity. *Mol Cell Biochem* **215**, 31-37 <https://doi.org/10.1023/a:1026558922596>.
- 30 Burwick, N.R., Wahl, M.L., Fang, J., Zhong, Z., Moser, T.L., Li, B., et al. (2005) An inhibitor of the  $F_1$  subunit of ATP synthase ( $IF_1$ ) modulates the activity of angiostatin on the endothelial cell surface. *J Biol Chem* **280**, 1740-1745 <https://doi.org/10.1074/jbc.M405947200>.
- 31 García, J.J., Morales-Ríos, E., Cortés-Hernández, P., Rodríguez-Zavala, J.S. (2006) The inhibitor protein ( $IF_1$ ) promotes dimerization of the mitochondrial  $F_1F_0$ -ATP synthase. *Biochemistry* **45**, 12695-12703 <https://doi.org/10.1021/bi060339j>.
- 32 Huang, L.J., Hsu, C., Tsai, T.N., Wang, S.J., Yang, R.C. (2007) Suppression of mitochondrial ATPase inhibitor protein ( $IF_1$ ) in the liver of late septic rats. *Biochim Biophys Acta* **1767**, 888-896 <https://doi.org/10.1016/j.bbabi.2007.03.009>.
- 33 Hall, A.M., Unwin, R.J., Parker, N., Duchon, M.R. (2009) Multiphoton imaging reveals differences in mitochondrial function between nephron segments. *J Am Soc Nephrol* **20**, 1293-1302 <https://doi.org/10.1681/asn.2008070759>.
- 34 Shah, D.I., Takahashi-Makise, N., Cooney, J.D., Li, L., Schultz, I.J., Pierce, E.L., et al. (2012) Mitochondrial Atpif1 regulates haem synthesis in developing erythroblasts. *Nature* **491**, 608-612 <https://doi.org/10.1038/nature11536>.

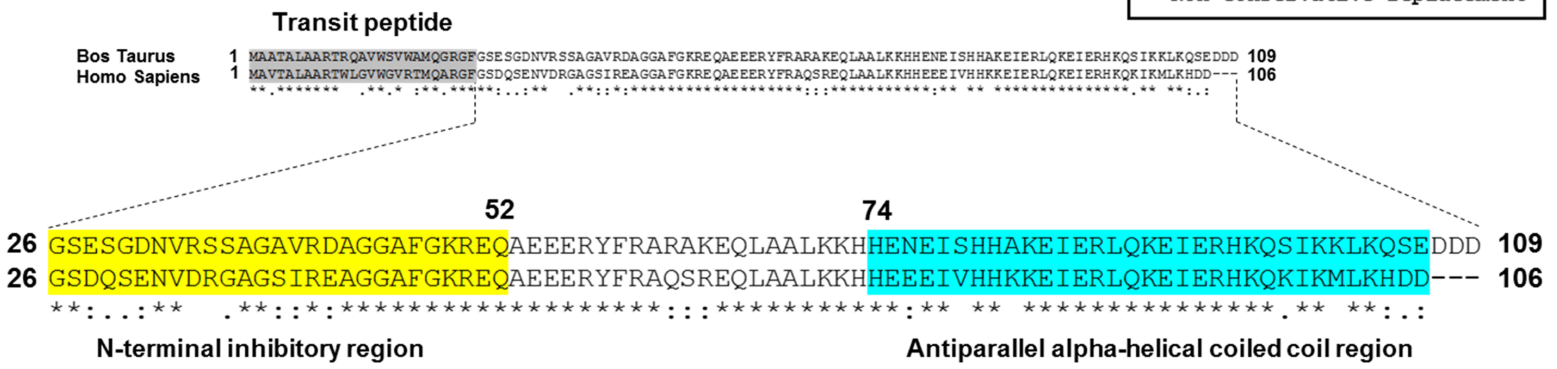
- 35 Faccenda, D., Tan, C.H., Seraphim, A., Duchen, M.R., Campanella, M. (2013) IF<sub>1</sub> limits the apoptotic-signalling cascade by preventing mitochondrial remodelling. *Cell Death Differ* **20**, 686-697 <https://doi.org/10.1038/cdd.2012.163>.
- 36 Lefebvre, V., Du, Q., Baird, S., Ng, A.C., Nascimento, M., Campanella, M., et al. (2013) Genome-wide RNAi screen identifies ATPase inhibitory factor 1 (ATPIF1) as essential for PARK2 recruitment and mitophagy. *Autophagy* **9**, 1770-1779 <https://doi.org/10.4161/auto.25413>.
- 37 O'Keeffe, B.A., Cilia, S., Maiyar, A.C., Vaysberg, M., Firestone, G.L. (2013) The serum- and glucocorticoid-induced protein kinase-1 (Sgk-1) mitochondria connection: identification of the IF-1 inhibitor of the F<sub>1</sub>F<sub>0</sub>-ATPase as a mitochondria-specific binding target and the stress-induced mitochondrial localization of endogenous Sgk-1. *Biochimie* **95**, 1258-1265 <https://doi.org/10.1016/j.biochi.2013.01.019>.
- 38 Formentini, L., Pereira, M.P., Sánchez-Cenizo, L., Santacatterina, F., Lucas, J.J., Navarro, C., et al. (2014) In vivo inhibition of the mitochondrial H<sup>+</sup>-ATP synthase in neurons promotes metabolic preconditioning. *Embo j* **33**, 762-778 <https://doi.org/10.1002/embj.201386392>.
- 39 Song, R., Song, H., Liang, Y., Yin, D., Zhang, H., Zheng, T., et al. (2014) Reciprocal activation between ATPase inhibitory factor 1 and NF-κB drives hepatocellular carcinoma angiogenesis and metastasis. *Hepatology* **60**, 1659-1673 <https://doi.org/10.1002/hep.27312>.
- 40 Chen, W.W., Birsoy, K., Mihaylova, M.M., Snitkin, H., Stasinski, I., Yucel, B., et al. (2014) Inhibition of ATPIF1 ameliorates severe mitochondrial respiratory chain dysfunction in mammalian cells. *Cell Rep* **7**, 27-34 <https://doi.org/10.1016/j.celrep.2014.02.046>.
- 41 Wu, J., Shan, Q., Li, P., Wu, Y., Xie, J., Wang, X. (2015) ATPase inhibitory factor 1 is a potential prognostic marker for the migration and invasion of glioma. *Oncol Lett* **10**, 2075-2080 <https://doi.org/10.3892/ol.2015.3548>.
- 42 Wei, S., Fukuhara, H., Kawada, C., Kurabayashi, A., Furihata, M., Ogura, S., et al. (2015) Silencing of ATPase inhibitory factor 1 inhibits cell growth via cell cycle arrest in bladder cancer. *Pathobiology* **82**, 224-232 <https://doi.org/10.1159/000439027>.
- 43 Yin, T., Lu, L., Xiong, Z., Wei, S., Cui, D. (2015) ATPase inhibitory factor 1 is a prognostic marker and contributes to proliferation and invasion of human gastric cancer cells. *Biomed Pharmacother* **70**, 90-96 <https://doi.org/10.1016/j.biopha.2014.12.036>.
- 44 Gao, Y.X., Chen, L., Hu, X.G., Wu, H.B., Cui, Y.H., Zhang, X., et al. (2016) ATPase inhibitory factor 1 expression is an independent prognostic factor in non-small cell lung cancer. *Am J Cancer Res* **6**, 1141-1148.
- 45 Faccenda, D., Nakamura, J., Gorini, G., Dhoot, G.K., Piacentini, M., Yoshida, M., et al. (2017) Control of mitochondrial remodeling by the ATPase inhibitory factor 1 unveils a pro-survival relay via OPA1. *Cell Rep* **18**, 1869-1883 <https://doi.org/10.1016/j.celrep.2017.01.070>.
- 46 Hardonnière, K., Fernier, M., Gallais, I., Mograbi, B., Podechard, N., Le Ferrec, E., et al. (2017) Role for the ATPase inhibitory factor 1 in the environmental carcinogen-induced Warburg phenotype. *Sci Rep* **7**, 195 <https://doi.org/10.1038/s41598-017-00269-7>.
- 47 Esparza-Moltó, P.B., Nuevo-Tapióles, C., Cuezva, J.M. (2017) Regulation of the H<sup>+</sup>-ATP synthase by IF<sub>1</sub>: a role in mitohormesis. *Cell Mol Life Sci* **74**, 2151-2166 <https://doi.org/10.1007/s00018-017-2462-8>.
- 48 Tanton, H., Voronina, S., Evans, A., Armstrong, J., Sutton, R., Criddle, D.N., et al. (2018) F<sub>1</sub>F<sub>0</sub>-ATP synthase inhibitory factor 1 in the normal pancreas and in pancreatic ductal adenocarcinoma: Effects on bioenergetics, invasion and proliferation. *Front Physiol* **9**, 833 <https://doi.org/10.3389/fphys.2018.00833>.
- 49 Martín-Jiménez, R., Faccenda, D., Allen, E., Reichel, H.B., Arcos, L., Ferraina, C., et al. (2018) Reduction of the ATPase inhibitory factor 1 (IF<sub>1</sub>) leads to visual impairment in vertebrates. *Cell Death Dis* **9**, 669 <https://doi.org/10.1038/s41419-018-0578-x>.
- 50 Kahancová, A., Sklenář, F., Ježek, P., Dlasková, A. (2018) Regulation of glucose-stimulated insulin secretion by ATPase Inhibitory Factor 1 (IF<sub>1</sub>). *FEBS Lett* **592**, 999-1009 <https://doi.org/10.1002/1873-3468.12991>.
- 51 Ding, X., Kong, J., Xu, W., Dong, S., Du, Y., Yao, C., et al. (2018) ATPase inhibitory factor 1 inhibition improves the antitumor of YC-1 against hepatocellular carcinoma. *Oncol Lett* **16**, 5230-5236 <https://doi.org/10.3892/ol.2018.9266>.
- 52 González-Llorente, L., Santacatterina, F., García-Aguilar, A., Nuevo-Tapióles, C. (2019) Overexpression of mitochondrial IF<sub>1</sub> prevents metastatic disease of colorectal cancer by enhancing anoikis and tumor infiltration of NK cells. **12**, <https://doi.org/10.3390/cancers12010022>.

- 53 Faccenda, D., Gorini, G., Jones, A., Thornton, C., Baracca, A., Solaini, G., et al. (2021) The ATPase Inhibitory Factor 1 (IF<sub>1</sub>) regulates the expression of the mitochondrial Ca<sup>2+</sup> uniporter (MCU) via the AMPK/CREB pathway. *Biochim Biophys Acta Mol Cell Res* **1868**, 118860 <https://doi.org/10.1016/j.bbamcr.2020.118860>.
- 54 Luciaková, K., Kuzela, S. (1984) Increased content of natural ATPase inhibitor in tumor mitochondria. *FEBS Lett* **177**, 85-88 [https://doi.org/10.1016/0014-5793\(84\)80986-2](https://doi.org/10.1016/0014-5793(84)80986-2).
- 55 Capuano, F., Guerrieri, F., Papa, S. (1997) Oxidative phosphorylation enzymes in normal and neoplastic cell growth. *J Bioenerg Biomembr* **29**, 379-384 <https://doi.org/10.1023/a:1022402915431>.
- 56 Bravo, C., Minauro-Sanmiguel, F., Morales-Ríos, E., Rodríguez-Zavala, J.S., García, J.J. (2004) Overexpression of the inhibitor protein IF<sub>1</sub> in AS-30D hepatoma produces a higher association with mitochondrial F<sub>1</sub>F<sub>0</sub> ATP synthase compared to normal rat liver: functional and cross-linking studies. *J Bioenerg Biomembr* **36**, 257-264 <https://doi.org/10.1023/b:jobb.0000031977.99479.ea>.
- 57 Cairns, R.A., Harris, I.S., Mak, T.W. (2011) Regulation of cancer cell metabolism. *Nat Rev Cancer* **11**, 85-95 <https://doi.org/10.1038/nrc2981>.
- 58 Hanahan, D., Weinberg, R.A. (2011) Hallmarks of cancer: the next generation. *Cell* **144**, 646-674 <https://doi.org/10.1016/j.cell.2011.02.013>.
- 59 Solaini, G., Sgarbi, G., Baracca, A. (2011) Oxidative phosphorylation in cancer cells. *Biochim Biophys Acta* **1807**, 534-542 <https://doi.org/10.1016/j.bbabi.2010.09.003>.
- 60 Zong, W.X., Rabinowitz, J.D., White, E. (2016) Mitochondria and cancer. *Mol Cell* **61**, 667-676 <https://doi.org/10.1016/j.molcel.2016.02.011>.
- 61 Warburg, O. (1956) On respiratory impairment in cancer cells. *Science* **124**, 269-270.
- 62 Moreno-Sánchez, R., Rodríguez-Enríquez, S., Marín-Hernández, A., Saavedra, E. (2007) Energy metabolism in tumor cells. *Febs j* **274**, 1393-1418 <https://doi.org/10.1111/j.1742-4658.2007.05686.x>.
- 63 Barger, J.F., Plas, D.R. (2010) Balancing biosynthesis and bioenergetics: metabolic programs in oncogenesis. *Endocr Relat Cancer* **17**, R287-304 <https://doi.org/10.1677/erc-10-0106>.
- 64 Wahlström, T., Henriksson, M.A. (2015) Impact of MYC in regulation of tumor cell metabolism. *Biochim Biophys Acta* **1849**, 563-569 <https://doi.org/10.1016/j.bbagr.2014.07.004>.
- 65 DeBerardinis, R.J., Lum, J.J., Hatzivassiliou, G., Thompson, C.B. (2008) The biology of cancer: metabolic reprogramming fuels cell growth and proliferation. *Cell Metab* **7**, 11-20 <https://doi.org/10.1016/j.cmet.2007.10.002>.
- 66 Pavlova, N.N., Thompson, C.B. (2016) The emerging hallmarks of cancer metabolism. *Cell Metab* **23**, 27-47 <https://doi.org/10.1016/j.cmet.2015.12.006>.
- 67 García-Bermúdez, J., Sánchez-Aragó, M., Soldevilla, B., Del Arco, A., Nuevo-Tapióles, C., Cuezva, J.M. (2015) PKA phosphorylates the ATPase inhibitory factor 1 and inactivates its capacity to bind and inhibit the mitochondrial H<sup>+</sup>-ATP synthase. *Cell Rep* **12**, 2143-2155 <https://doi.org/10.1016/j.celrep.2015.08.052>.
- 68 Runswick, M.J., Bason, J.V., Montgomery, M.G., Robinson, G.C., Fearnley, I.M., Walker, J.E. (2013) The affinity purification and characterization of ATP synthase complexes from mitochondria. *Open Biol* **3**, 120160 <https://doi.org/10.1098/rsob.120160>.
- 69 Harris, D.A., von Tscharner, V., Radda, G.K. (1979) The ATPase inhibitor protein in oxidative phosphorylation. The rate-limiting factor to phosphorylation in submitochondrial particles. *Biochim Biophys Acta* **548**, 72-84 [https://doi.org/10.1016/0005-2728\(79\)90188-9](https://doi.org/10.1016/0005-2728(79)90188-9).
- 70 Lippe, G., Sorgato, M.C., Harris, D.A. (1988) Kinetics of the release of the mitochondrial inhibitor protein. Correlation with synthesis and hydrolysis of ATP. *Biochim Biophys Acta* **933**, 1-11 [https://doi.org/10.1016/0005-2728\(88\)90050-3](https://doi.org/10.1016/0005-2728(88)90050-3).
- 71 Arslanbaeva, L.R., Santoro, M.M. (2020) Adaptive redox homeostasis in cutaneous melanoma. *Redox Biol* **37**, 101753 <https://doi.org/10.1016/j.redox.2020.101753>.
- 72 Weinberg, F., Chandel, N.S. (2009) Reactive oxygen species-dependent signaling regulates cancer. *Cell Mol Life Sci* **66**, 3663-3673 <https://doi.org/10.1007/s00018-009-0099-y>.
- 73 Cheng, C.W., Kuo, C.Y., Fan, C.C., Fang, W.C., Jiang, S.S., Lo, Y.K., et al. (2013) Overexpression of Lon contributes to survival and aggressive phenotype of cancer cells through mitochondrial complex I-mediated generation of reactive oxygen species. *Cell Death Dis* **4**, e681 <https://doi.org/10.1038/cddis.2013.204>.

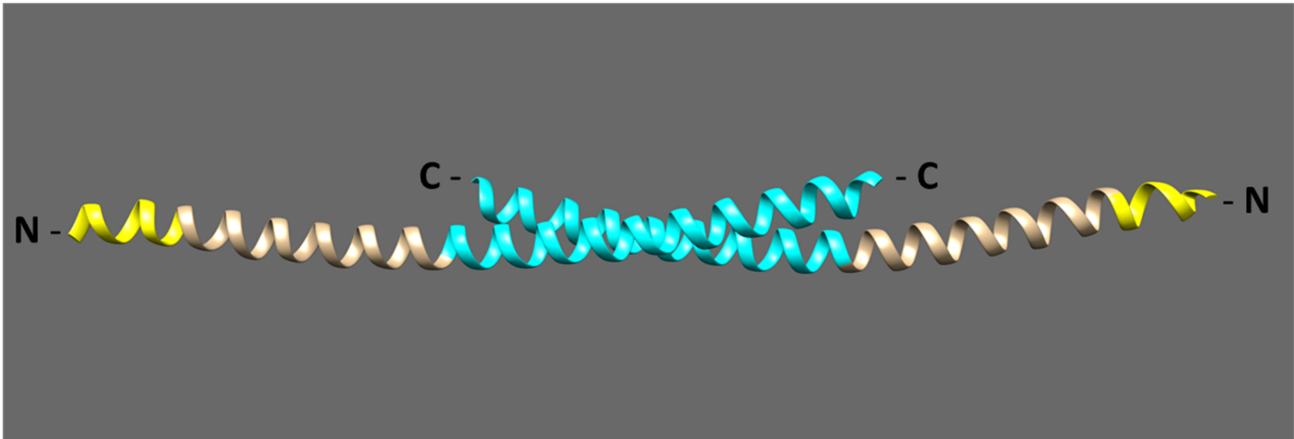
- 74 Diebold, L.,Chandel, N.S. (2016) Mitochondrial ROS regulation of proliferating cells. *Free Radic Biol Med* **100**, 86-93 <https://doi.org/10.1016/j.freeradbiomed.2016.04.198>.
- 75 Sies, H.,Jones, D.P. (2020) Reactive oxygen species (ROS) as pleiotropic physiological signalling agents. *Nat Rev Mol Cell Biol* **21**, 363-383 <https://doi.org/10.1038/s41580-020-0230-3>.
- 76 Sabharwal, S.S.,Schumacker, P.T. (2014) Mitochondrial ROS in cancer: initiators, amplifiers or an Achilles' heel? *Nat Rev Cancer* **14**, 709-721 <https://doi.org/10.1038/nrc3803>.
- 77 Kwon, S., Ko, H., You, D.G.,Kataoka, K. (2019) Nanomedicines for reactive oxygen species mediated approach: an emerging paradigm for cancer treatment. **52**, 1771-1782 <https://doi.org/10.1021/acs.accounts.9b00136>.
- 78 Thomas, L.W., Stephen, J.M., Esposito, C., Hoer, S., Antrobus, R., Ahmed, A., et al. (2019) CHCHD4 confers metabolic vulnerabilities to tumour cells through its control of the mitochondrial respiratory chain. **7**, 2 <https://doi.org/10.1186/s40170-019-0194-y>.
- 79 Zou, Z., Chang, H., Li, H.,Wang, S. (2017) Induction of reactive oxygen species: an emerging approach for cancer therapy. *Apoptosis* **22**, 1321-1335 <https://doi.org/10.1007/s10495-017-1424-9>.
- 80 Sgarbi, G., Gorini, G., Costanzini, A., Barbato, S., Solaini, G.,Baracca, A. (2017) Hypoxia decreases ROS level in human fibroblasts. *Int J Biochem Cell Biol* **88**, 133-144 <https://doi.org/10.1016/j.biocel.2017.05.005>.
- 81 Kelso, G.F., Porteous, C.M., Coulter, C.V., Hughes, G., Porteous, W.K., Ledgerwood, E.C., et al. (2001) Selective targeting of a redox-active ubiquinone to mitochondria within cells: antioxidant and antiapoptotic properties. *J Biol Chem* **276**, 4588-4596 <https://doi.org/10.1074/jbc.M009093200>.
- 82 Halliwell, B.,Gutteridge, J.M. (1984) Oxygen toxicity, oxygen radicals, transition metals and disease. *Biochem J* **219**, 1-14 <https://doi.org/10.1042/bj2190001>.
- 83 Baker, M.J., Lampe, P.A., Stojanovski, D., Korwitz, A., Anand, R., Tatsuta, T., et al. (2014) Stress-induced OMA1 activation and autocatalytic turnover regulate OPA1-dependent mitochondrial dynamics. *Embo j* **33**, 578-593 <https://doi.org/10.1002/embj.201386474>.

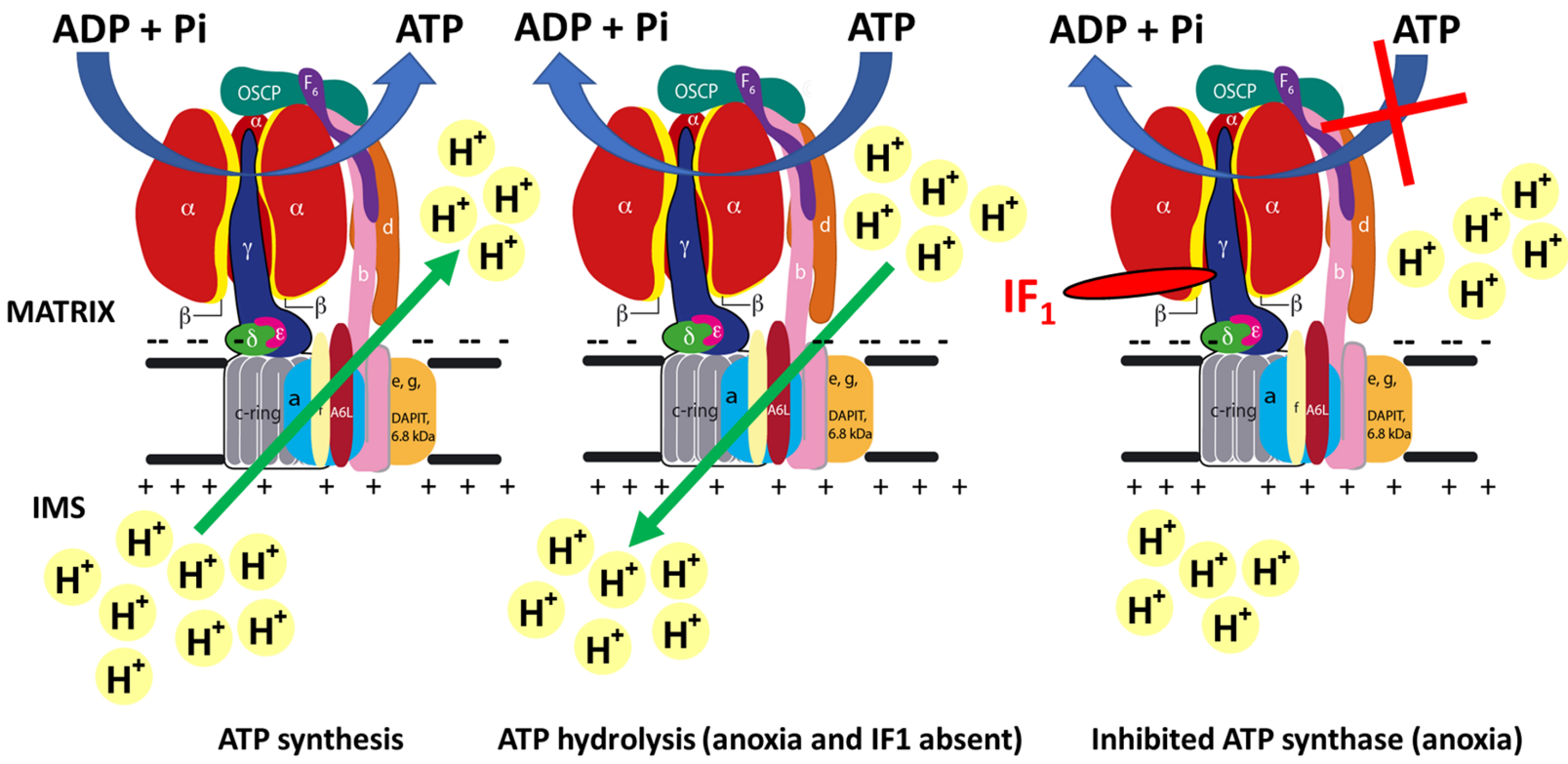
**A**

\* Identity  
 : Conservative replacement  
 . Semiconservative replacement  
 Non-conservative replacement



**B**

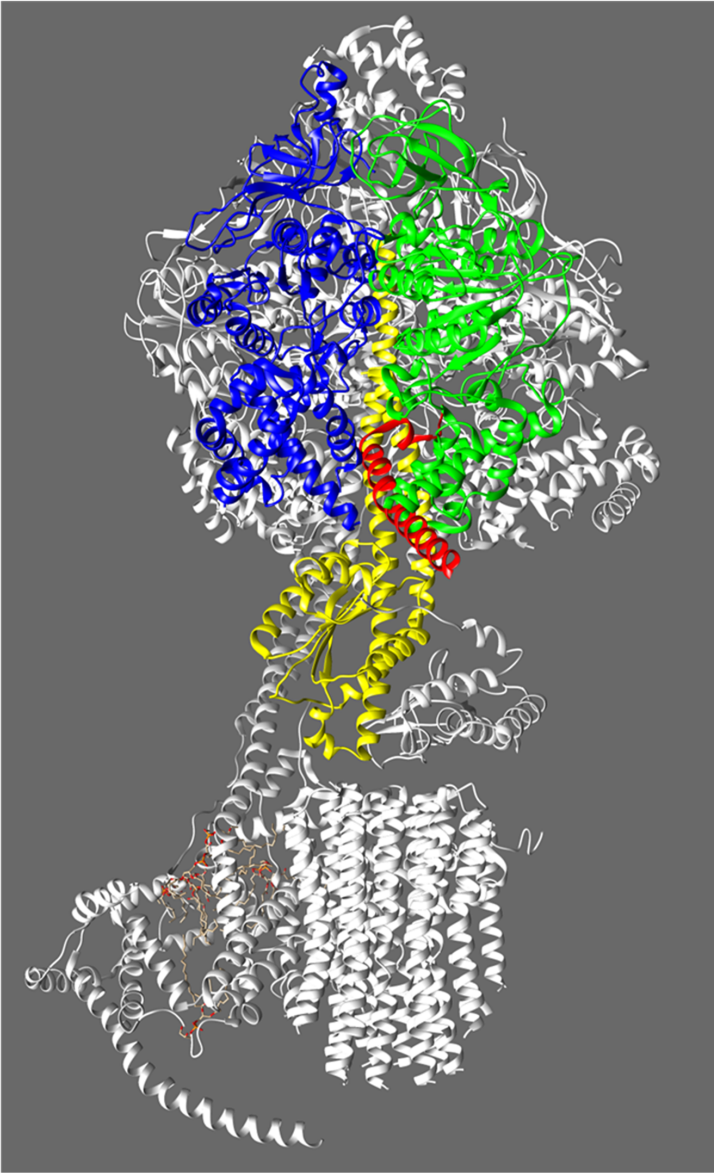




ATP synthesis

ATP hydrolysis (anoxia and IF1 absent)

Inhibited ATP synthase (anoxia)

**A****B**