Evaluation of intramitochondrial ATP levels identifies G0/G1 switch gene 2 as a positive regulator of oxidative phosphorylation

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Edited by Gottfried Schatz, University of Basel, Reinach, Switzerland, and approved November 19, 2013 (received for review October 7, 2013)

The oxidative phosphorylation (OXPHOS) system generates most of the ATP in respiring cells. ATP-depleting conditions, such as hypoxia, trigger responses that promote ATP production. However, how OXPHOS is regulated during hypoxia has yet to be elucidated. In this study, selective measurement of intramitochondrial ATP levels identified the hypoxia-inducible protein G0/G1 switch gene 2 (G0s2) as a positive regulator of OXPHOS. A mitochondria-targeted, FRET-based ATP biosensor enabled us to assess OXPHOS activity in living cells. Mitochondria-targeted, FRET-based ATP biosensor and ATP production assay in a semi-intact cell system revealed that G0s2 increases mitochondrial ATP production. The expression of G0s2 was rapidly and transiently induced by hypoxic stimuli, and G0s2 interacts with OXPHOS complex V (F_oF_1-ATP synthase). Furthermore, physiological enhancement of G0s2 expression prevented cells from ATP depletion and induced a cellular tolerance for hypoxic stress. These results show that G0s2 positively regulates OXPHOS activity by interacting with F_oF_1-ATP synthase, which causes an increase in ATP production in response to hypoxic stress and protects cells from a critical energy crisis. These findings contribute to the understanding of a unique stress response to energy depletion. Additionally, this study shows the importance of assessing intramitochondrial ATP levels to evaluate OXPHOS activity in living cells.

energy metabolism | live-cell imaging

Maintaining cellular homeostasis and activities requires a stable energy supply. Most eukaryotic cells generate ATP as their energy currency mainly through the mitochondrial oxidative phosphorylation (OXPHOS) system. The OXPHOS system consists of five large protein complex units (i.e., complexes I–V), comprising more than 100 proteins. In this system, oxygen (O_2) is essential as the terminal electron acceptor for complex IV to finally produce the proton-motive force that drives the ATP-generating molecular motor complex V (F_oF_1-ATP synthase).

Hypoxia causes the depletion of intracellular ATP and triggers adaptive cellular responses to help maintain intracellular ATP levels and minimize any deleterious effects of energy depletion. Although the metabolic switch from mitochondrial respiration to anaerobic glycolysis is widely recognized (1–4), several recent reports have shown that hypoxic stimuli unexpectedly increase OXPHOS efficiency as well (5–7). In other words, cells have adaptive mechanisms to maintain intracellular ATP levels by enhancing OXPHOS, particularly in the early phase of hypoxia, in which the O_2 supply is limited but still remains. However, the mechanism by which OXPHOS is regulated during this early hypoxic phase is still not fully understood.

Revealing the mechanism of this fine-tuned regulation of OXPHOS requires accurate and noninvasive measurements of OXPHOS activity. Although researchers have established methods to measure OXPHOS activity, precise measurement, especially in living cells, is still difficult. Measuring the intracellular ATP concentration is one of the most commonly used methods for evaluating OXPHOS activity. However, there are two major problems with this method. First, the intracellular ATP concentration does not always accurately reflect OXPHOS activity, because it can also be affected by glycolytic ATP production, cytosolic ATPases, and ATP buffering enzymes, such as creatine kinase and adenylate kinase (8). Second, because measurements of the ATP concentration by chromatography (9), MS (10), NMR (11), or luciferase assays (12) are based on cell extract analysis, these methods cannot be used to measure the serial ATP concentration changes in living cells in real time.

In this study, we overcame these problems by the selective measurement of the intramitochondrial matrix ATP concentration ($[ATP]_{mito}$) in living cells. In the final step of OXPHOS, ATP is produced not in the cytosol but in the mitochondrial matrix. Therefore, we hypothesized that a selectively measuring $[ATP]_{mito}$ is suitable for the highly sensitive evaluation of cellular ATP production by OXPHOS. In fact, real-time evaluation of both $[ATP]_{mito}$ and the cytosolic ATP concentration ($[ATP]_{cyto}$) in living cells revealed that $[ATP]_{mito}$ reflected OXPHOS activity with far more sensitivity than $[ATP]_{cyto}$. Using this fine method, we found that G0/G1 switch gene 2 (G0s2), a hypoxia-induced

Significance

We developed a sensitive method to assess the activity of oxidative phosphorylation in living cells using a FRET-based ATP biosensor. We then revealed that G0/G1 switch gene 2, a protein rapidly induced by hypoxia, increases mitochondrial ATP production by interacting with F_oF_1-ATP synthase and protects cells from a critical energy crisis.

Author contributions: Y.A. and S.T. designed research; H. Kioka, H. Kato, O.T., and A.N. performed research; M.F., T.S., H.I., S.H., S.Y., T. Matsuzaki, K.T., H.A., M.A., T. Minamino, Y.S., M.Y., H.N., M.K., and I.K. contributed new reagents/analytic tools; H. Kioka and H. Kato analyzed data; and Y.A. and S.T. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1318547111/-/DCSupplemental.

protein in cardiomyocytes, increases OXPHOS activity. G0s2 interacted with F_oF_1-ATP synthase and increased the ATP production rate. Our results suggest that hypoxia-induced protein G0s2 is a positive regulator of OXPHOS and protects cells by preserving ATP production, even under hypoxic conditions.

Results

Establishment of a Sensitive Method to Assess OXPHOS Activity in Living Cells. To elucidate the mechanism by which OXPHOS is regulated under hypoxia, it is essential to establish a sensitive method for assessing OXPHOS activity in living cells. For this purpose, we used an ATP indicator based on ε-subunit for analytical measurements (ATeam), which is an ATP-sensing FRET-based indicator (13). We introduced this ATP biosensor into cardiomyocytes that possess an abundance of mitochondria and produce the highest levels of ATP among all primary cells (14, 15). The ATeam assay can measure both $[ATP]_{cyto}$ (i.e., the Cyto-ATeam assay) and $[ATP]_{mito}$ when a duplex of the mitochondrial targeting signal of cytochrome *c* oxidase subunit VIII is attached to the indicator (i.e., the Mit-ATeam assay). In this case, the YFP/CFP emission ratio of the ATeam fluorescence represents the ATP concentration in each compartment. Interestingly, the Mit-ATeam assay was a far more sensitive method than the Cyto-ATeam assay in determining OXPHOS activity in living cells. For example, a very low dose of oligomycin A (0.01 μg/mL), a specific OXPHOS complex V (F_oF_1-ATP synthase) inhibitor, greatly reduced the YFP/CFP emission ratio of the Mit-ATeam fluorescence that represents $[ATP]_{mito}$ within 10 min (Fig. 1 *A*, *Upper* and *B* and Movie S1). In contrast, the same dose of oligomycin A resulted in a slight and slow decline of the YFP/CFP emission ratio of Cyto-ATeam fluorescence (Fig. 1 *A*, *Lower* and *B* and Movie S1). The same phenomenon was observed when the cells were exposed to hypoxia, which suppresses the activity of OXPHOS complex IV (cytochrome *c* oxidase). Again, $[ATP]_{mito}$ decreased more markedly than $[ATP]_{cyto}$ during 2.5 h of hypoxia (Fig. 1 *C* and *D* and Movie S2). These results indicate that the Mit-ATeam assay is far more sensitive for measuring the activity of OXPHOS than the Cyto-ATeam assay. In addition, OXPHOS inhibition decreased the YFP/CFP emission ratio of the Mit-ATeam fluorescence of HeLa cells as well as cardiomyocytes (Fig. S1), suggesting the broad applicability of this assay. Therefore, we used Mit-ATeam for the assessment of the OXPHOS activity in living cells.

Hypoxia-Induced Gene G0s2 Affects the Intramitochondrial ATP Concentration. The expression of genes involved in OXPHOS regulation is considered to be up-regulated in the early phase of hypoxia. Thus, to find unique OXPHOS regulators, we focused on the rapidly induced genes in response to hypoxic stimulation. We compared the gene expression profiles of cultured rat cardiomyocytes at three different time points during hypoxic conditions (0, 2, and 12 h) (Fig. S2*A*). The expression of well-known hypoxia-induced genes, such as VEGF-α and hexokinase 2 mRNA (16, 17), was slightly up-regulated at 2 h and further enhanced at 12 h of hypoxia. In contrast, three other genes (*Adamts1*, *Cdkn3*, and *G0s2*) underwent rapid increases in expression at 2 h but declined at 12 h of sustained hypoxia (Fig. S2 *B* and *C*). This rapid and transient time course of expression implies that these three genes may play distinct regulatory roles, especially in the early hypoxic phase, in which oxygen is limited but still available. To examine whether these genes are involved in the regulation of OXPHOS activity, we knocked down these genes by shRNA (see Fig. S7*A*) and examined $[ATP]_{mito}$ using the Mit-ATeam assay. In this experiment, $[ATP]_{mito}$ in cardiomyocytes treated with shRNA for G0s2 clearly declined within 24 h compared with the control cardiomyocytes (Fig. 2*A* and Movie S3). In addition, the time course of ATP decline was in agreement with the time course of G0s2 depletion (Fig. 2*A* and Fig. S3*A*). Importantly, the overexpression of G0s2 restored normal ATP levels (Fig. 2 *B* and *C*), and again, the Cyto-ATeam assay could not detect a significant effect of G0s2 knockdown within this time frame (Fig. S3*B* and Movie S4). These findings imply that mitochondrial ATP production through OXPHOS was inhibited by G0s2 ablation. We confirmed that the mRNA and protein levels of G0s2 both increased after 2–6 h of hypoxia and then declined after 12 h of hypoxia (Fig. 2 *D* and *E*). G0s2 was first reported as a gene with

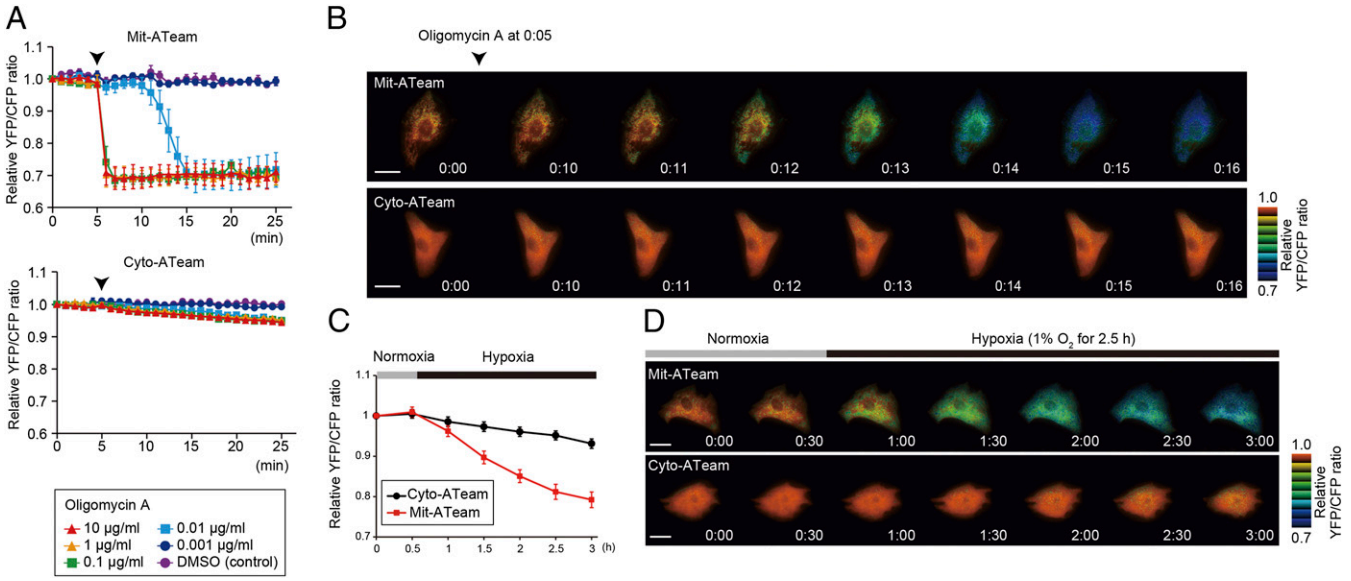

Fig. 1. Establishment of a sensitive method to assess OXPHOS activity in living cells. (*A*) YFP/CFP emission ratio plots of (*Upper*) Mit-ATeam and (*Lower*) Cyto-ATeam fluorescence in cardiomyocytes. Various concentrations (0.001, 0.01, 0.1, 1, and 10 μg/mL) of oligomycin A or DMSO (control) were added at 5 min (arrowhead; $n = 3$). (*B*) Representative sequential YFP/CFP ratiometric pseudocolored images of (*Upper*) Mit-ATeam and (*Lower*) Cyto-ATeam in cardiomyocytes. Oligomycin A (0.01 μg/mL) was added at 5 min. (Scale bars: 20 μm.) (*C*) YFP/CFP emission ratio plots of Mit-ATeam and Cyto-ATeam fluorescence in cardiomyocytes ($n = 10$). (*D*) Representative sequential YFP/CFP ratiometric pseudocolored images of (*Upper*) Mit-ATeam and (*Lower*) Cyto-ATeam in cardiomyocytes. Cells were exposed to 1% hypoxia from the time point 30 min. All of the measurements were normalized to the YFP/CFP emission ratio at 0 min. Data are represented as the means ± SEMs. (Scale bars: 20 μm.)

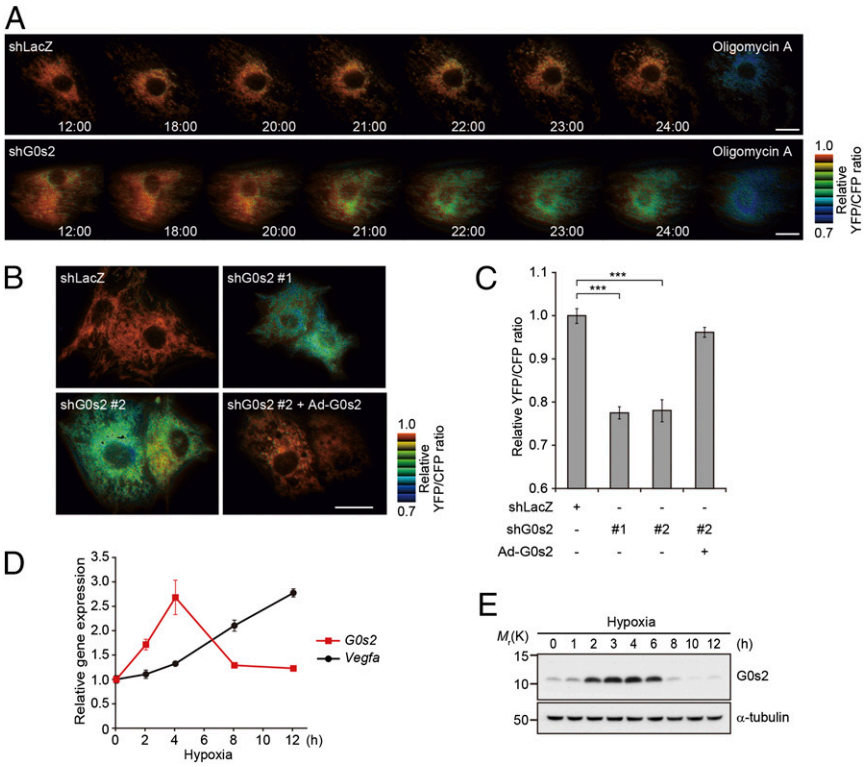

Fig. 2. G0s2, a hypoxia-inducible protein, affects intramitochondrial ATP concentration in cardiomyocytes. (*A*) Sequential YFP/CFP ratiometric pseudocolored images of Mit-ATeam fluorescence in cardiomyocytes expressing (*Upper*) shRNAs for LacZ (shLacZ) or (*Lower*) G0s2 (shG0s2). Oligomycin A (1 μg/mL) was added at the end of the time-lapse imaging to completely inhibit ATP synthesis. The indicated time represents the period after adenovirus infection. (*B*) Representative YFP/CFP ratiometric pseudocolored images of Mit-ATeam fluorescence in cardiomyocytes expressing the indicated adenovirus for 24 h. (Scale bar: *A* and *B*, 20 μm.) (*C*) The bar graph shows the mean YFP/CFP emission ratio of Mit-ATeam fluorescence in cardiomyocytes expressing shLacZ ($n = 30$), shG0s2 #1 ($n = 30$), shG0s2 #2 ($n = 29$), and shG0s2 #2 + G0s2 WT ($n = 32$) for 24 h. All of the measurements were normalized to the average of the control cells (shLacZ). $***P < 0.001$. (*D*) Gene expression value plots of *G0s2* (red line) and *VEGF-α* (*Vegfa*; black line) levels in cardiomyocytes under hypoxic conditions (1% O_2). Each value was compared with the level of *Actb* expression ($n = 3$). Values represent the means ± SEMs. (*E*) Immunoblotting of the G0s2 expression in cardiomyocytes under hypoxic conditions (1% O_2).

expression that was induced during the cell cycle switch from G0 to G1 phase (18). G0s2 is expressed in many tissues and especially abundant in heart, skeletal muscle, liver, kidney, brain, and adipose tissue (19). Although G0s2 may play a role in cell cycle progression (20), the function of G0s2 in the hypoxic response remains unknown.

G0s2 Rescues the Decline of ATP Production During Hypoxia. We next tested whether the overexpression of the G0s2 before hypoxic stress could prevent hypoxia-induced ATP depletion. We prepared cardiomyocytes overexpressing G0s2 and control cardiomyocytes. During sustained hypoxia, $[ATP]_{mito}$ gradually declined in control cardiomyocytes as measured by the Mit-ATeam assay. Notably, the overexpression of G0s2 before the onset of hypoxia reduced this decline in $[ATP]_{mito}$, which allowed the cardiomyocytes to promptly recover to baseline levels of $[ATP]_{mito}$ after reoxygenation (Fig. 3 *A* and *B* and Movie S5). In addition, the prehypoxia overexpression of G0s2 preserved cell viability during sustained hypoxia (Fig. 3*C*). These results suggest that G0s2 can preserve mitochondrial ATP production even under hypoxia and protect cells from the energy crisis under hypoxia.

G0s2 Binds to F_oF_1-ATP Synthase but Not Other OXPHOS Protein Complexes. To reveal the mechanism by which G0s2 affects $[ATP]_{mito}$, we sought to identify the biochemical targets of G0s2. We screened for G0s2 binding proteins by immunoaffinity purification of cell lysates from cardiomyocytes expressing C-terminally Flag-tagged G0s2 (G0s2-Flag). G0s2-Flag is expressed in cardiomyocytes localized to the mitochondria (Fig. S4*A*). MS analysis revealed that multiple F_oF_1-ATP synthase subunits, but no other mitochondrial respiratory chain complex subunits, were coimmunoprecipitated with G0s2-Flag (Fig. S4*B* and Table S1). F_oF_1-ATP synthase is a well-known ATP-producing enzyme composed of a protein complex that contains an extramembranous F_1 and an intramembranous F_o domain linked by a peripheral and a central stalk (21–24). The binding of F_oF_1-ATP synthase to G0s2-Flag was confirmed by immunoblotting with antibodies against several subunits of F_oF_1-ATP synthase (Fig. 4*A*).

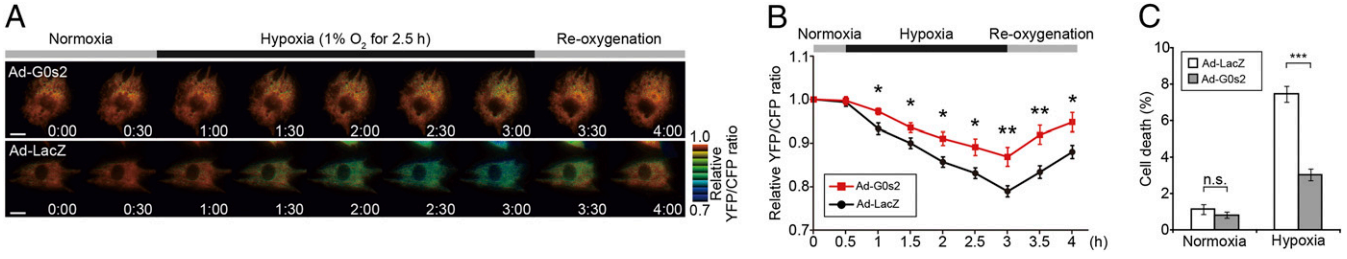

Fig. 3. Overexpression of G0s2 before hypoxia rescues the decline of mitochondrial ATP production during hypoxia. (*A*) Sequential YFP/CFP ratiometric pseudocolored images of Mit-ATeam fluorescence in cardiomyocytes expressing (*Upper*) G0s2 WT or (*Lower*) LacZ during hypoxia and reoxygenation. (Scale bar: 20 μm.) (*B*) YFP/CFP emission ratio plots of Mit-ATeam fluorescence in cardiomyocytes expressing G0s2 WT ($n = 20$) or LacZ ($n = 19$) during hypoxia and reoxygenation. All of the measurements were normalized to the ratio at time 0 and compared between cardiomyocytes with G0s2 WT and LacZ at each time point. (*C*) The bar graph shows the cell viability of cardiomyocytes overexpressing G0s2 under hypoxic conditions. Cardiomyocytes expressing either LacZ or G0s2 WT were cultured under normoxic or hypoxic conditions for 18 h ($n = 8$). The asterisks denote statistical significance comparing G0s2 with LacZ. Data are represented as the means ± SEMs. n.s., not significant. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Conversely, G0s2-Flag was coimmunoprecipitated with F_oF_1-ATP synthase (Fig. S4*C*). G0s2-Flag was also found to be associated with the F_oF_1-ATP synthase in 293T and HeLa cells (Fig. S4*C*). Both coimmunoprecipitation using an anti-G0s2 antibody and a reciprocal immunoprecipitation revealed that endogenous G0s2 interacts with F_oF_1-ATP synthase, whereas none of the proteins in complexes I–IV or adenine nucleotide translocase 1 (ANT1; also referred to as ADP/ATP carrier) were coimmunoprecipitated with G0s2 (Fig. 4 *B* and *C*).

Given that the G0s2 protein contains an evolutionarily conserved amino terminus and one hydrophobic domain (HD) (19), we created three G0s2 partial deletion mutants to identify the domain in G0s2 that is important for binding to F_oF_1-ATP synthase (Fig. S4*D*). Among these mutants, G0s2 ΔC and G0s2 ΔN but not G0s2 ΔHD bound to the F_oF_1-ATP synthase complex (Fig. 4*D* and Fig. S4 *E* and *F*). Furthermore, we confirmed that G0s2 directly interacts with F_oF_1-ATP synthase in an in vitro pull-down assay using a recombinant maltose-binding protein–fused G0s2 protein and purified F_oF_1-ATP synthase from bovine heart mitochondria (Fig. S5). Immunocytochemical analysis revealed that endogenous G0s2 colocalized with the β-subunit of F_oF_1-ATP synthase (Fig. 4*E*). The knockdown of G0s2 expression by shRNA abolished G0s2 staining (Figs. S6 and S7*A*), indicating that both antibodies used for immunostaining specifically recognize G0s2. These data suggest that G0s2 interacts with the F_oF_1-ATP synthase complex through its HD in mitochondria and regulates OXPHOS activity.

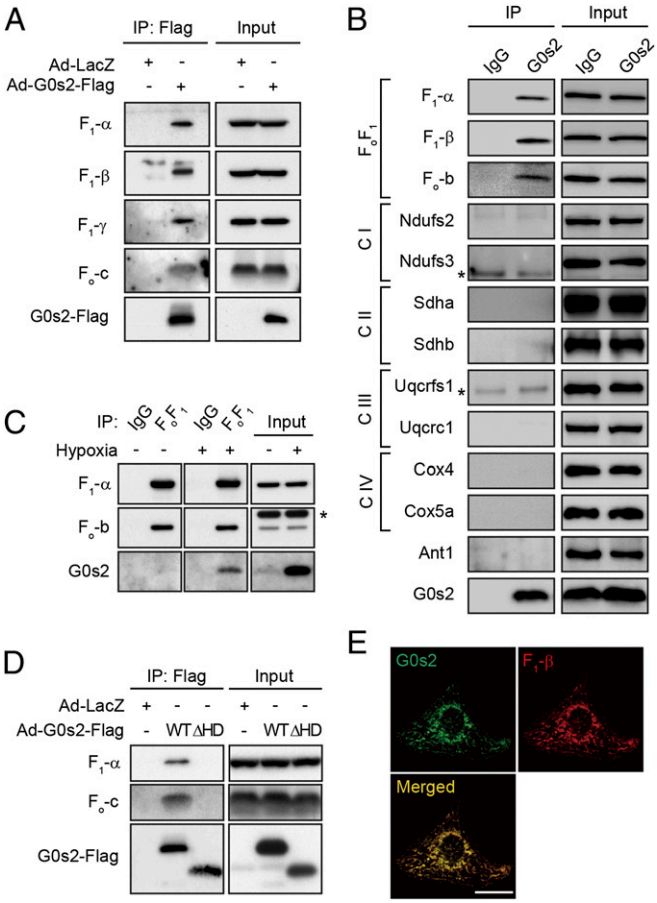

Fig. 4. G0s2 interacts with the F_oF_1-ATP synthase in mitochondria. (*A*) Immunoprecipitation (IP) of G0s2-Flag in cardiomyocytes. Cell lysates from cardiomyocytes expressing G0s2-Flag or LacZ were immunoprecipitated with an anti-Flag antibody. (*B*) IP of endogenous G0s2 in cardiomyocytes. Endogenous G0s2 was induced by hypoxia and immunoprecipitated using an anti-G0s2 antibody. C, OXPHOS complex; F_oF_1, F_oF_1-ATP synthase. *IgG light chain. (*C*) IP of F_oF_1-ATP synthase in cardiomyocytes under normoxic or hypoxic conditions. Cell lysates from cardiomyocytes cultured under normoxia or hypoxia for 4 h were immunoprecipitated with an antibody against the whole F_oF_1-ATP synthase complex or a control IgG. *Nonspecific band. (*D*) IP of G0s2 mutants expressed in cardiomyocytes. Cell lysates were immunoprecipitated with an anti-Flag antibody. (*E*) Immunostained images of hypoxia-stimulated (4 h) cardiomyocytes with anti-G0s2 (green) and anti–F_oF_1-ATP synthase β-subunit (red) antibodies. (Scale bars: 20 μm.)

G0s2 Increases Mitochondrial ATP Production Rate. $[ATP]_{mito}$ is mainly determined by the rate of ATP synthesis by F_oF_1-ATP synthase and ATP/ADP exchange by the ATP/ADP translocase ANT1. This theory means that the increased $[ATP]_{mito}$ observed in the G0s2-overexpressing cells may result from the increased ATP synthesis and/or decreased ATP/ADP exchange, although G0s2 did not interact with ANT1 (Fig. 4*B*). To resolve this issue and directly measure the rate of ATP production in mitochondria, we used a semiintact cell system called the mitochondrial activity of streptolysin O permeabilized cells (MASC) assay (25). In this assay, we permeabilized the plasma membrane to wash out any cytosolic components, such as creatine and glycolytic substrates, but left the mitochondria intact. Furthermore, we treated the cells with P^1, P^5-di(adenosine-5′) pentaphosphate to inhibit the activity of adenylate kinase. These steps allowed us to measure the ATP production rate mostly from OXPHOS, with a minimal contribution of ATP buffering systems in the cytosol. The MASC assay was suitable for accurate measurement of mitochondrial ATP production rate, because mitochondria in this semiintact cell system suffered much smaller damage than the isolated mitochondria in the conventional method. Surprisingly, in the MASC assay, the ATP production rate markedly increased when G0s2 was expressed in HeLa cells that lacked endogenous G0s2 (Fig. 5*A*). In cardiomyocytes, shRNA-mediated G0s2 knockdown decreased the ATP production rate in mitochondria, and the expression of G0s2 WT but not G0s2 ΔHD could restore the ATP production rate (Fig. 5*B* and Fig. S7*A*). In both cells, complete inhibition of ATP production by oligomycin A indicated that the observed ATP synthesis was catalyzed by OXPHOS but not other metabolism (Fig. 5 *A* and *B*).

Next, to evaluate the physiological role of G0s2, we examined whether endogenous G0s2 induced by hypoxia could enhance the ATP production rate. Cardiomyocytes were pretreated with hypoxia for 4 h, during which G0s2 expression was largely induced. We then evaluated the ATP production rate of both hypoxia-pretreated and nontreated cardiomyocytes under room air conditions. Even under these equivalent normoxic conditions, hypoxia-pretreated cardiomyocytes produced ATP faster than nontreated control cardiomyocytes (Fig. 5*C* and Fig. S7*B*). G0s2 knockdown attenuated this increase in the rate of ATP production, indicating that the enhanced ATP production rate resulting from hypoxia pretreatment primarily depends on endogenous G0s2 induction. This increased G0s2 expression was essential for cell survival, because G0s2-depleted cells died earlier than control cells under conditions of hypoxic stress (Fig. 5*D*)

Furthermore, to assess the effect of G0s2 on cellular respiration, we continuously measured the oxygen consumption rate (OCR) using an XF96 Extracellular Flux Analyzer. G0s2 knockdown decreased the basal OCR of cardiomyocytes, most likely because of the decreased activity of ATP synthesis (Fig. 5 *E* and *F*). In contrast, the proton leakage of the mitochondrial inner membrane and the maximum respiratory capacity of OXPHOS complexes I–IV were unaffected by G0s2 ablation (Fig. 5 *E* and *F*). These data show that G0s2 knockdown reduced respiration caused by ATP synthesis without affecting respiration caused by proton leakage, nonmitochondrial respiration, or the maximal respiration capacity.

All these findings indicate that G0s2 enhances the mitochondrial ATP production rate by increasing the activity of F_oF_1-ATP synthase.

Discussion

In this study, we showed that G0s2 kinetically increased OXPHOS activity through direct binding to F_oF_1-ATP synthase. Our previous

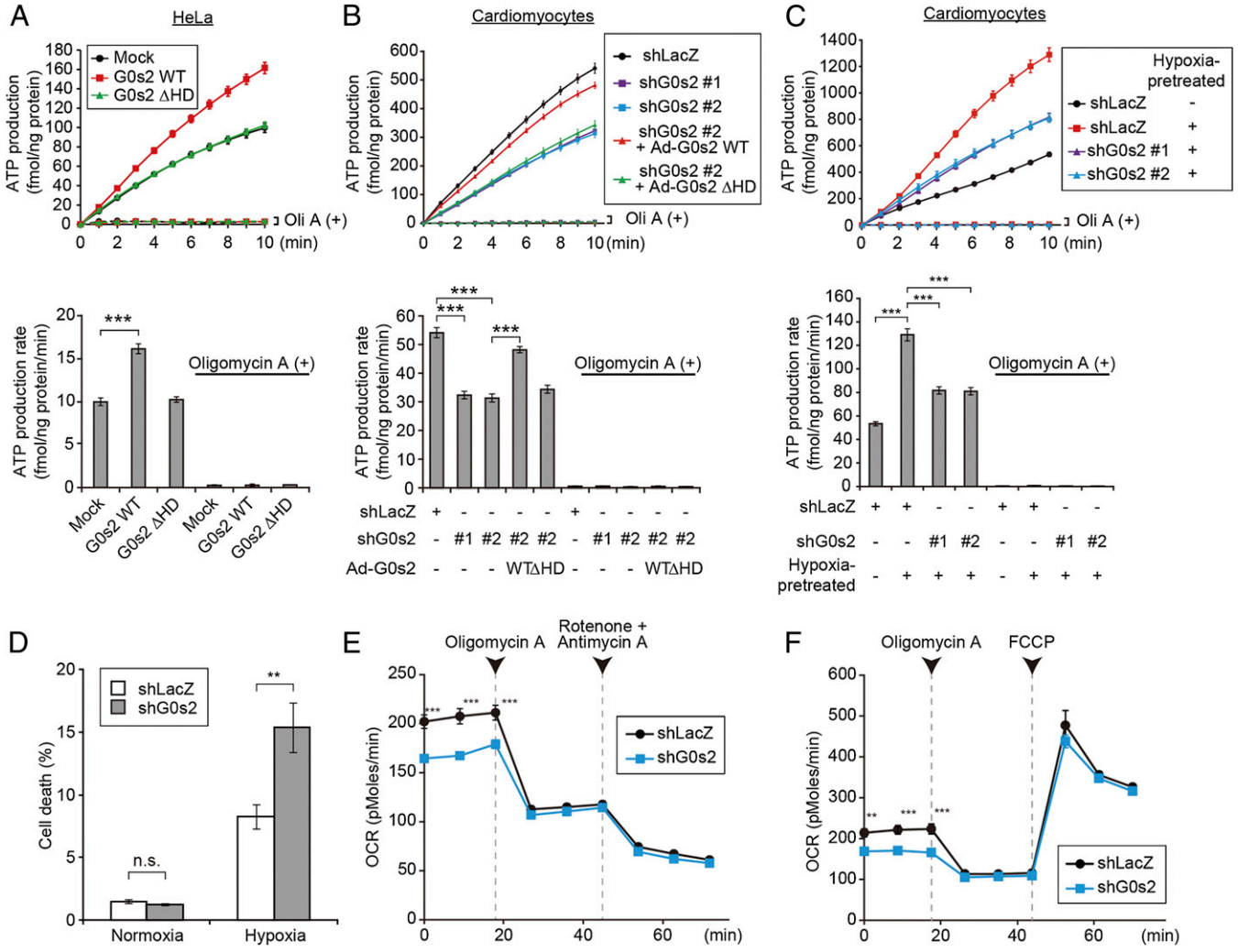

Fig. 5. G0s2 enhances the mitochondrial ATP production rate. (*A* and *B*) MASC assay of (*A*) permeabilized HeLa cells expressing the indicated plasmids or (*B*) cardiomyocytes expressing the indicated adenovirus in the presence (dotted lines) or absence (solid lines) of 1 μg/mL oligomycin A (Oli A). *Upper* shows the ATP production plots, and *Lower* shows the mean ATP production rates between 0 and 10 min. (*A*) $n = 12$. (*B*) Solid lines, $n = 12$; dotted lines, $n = 8$. (*C*) MASC assay of permeabilized cardiomyocytes pretreated with hypoxia. Cells expressing the indicated adenovirus were pretreated with or without hypoxia for 4 h. After the pretreatment, the cells were permeabilized under room air conditions followed by MASC assay in the presence (dotted lines; $n = 8$) or absence (solid lines; $n = 12$) of 1 μg/mL Oli A. *Upper* shows the ATP production plot, and *Lower* shows the mean ATP production rate between 0 and 10 min. (*D*) The bar graph represents the cell viability of G0s2-depleted cardiomyocytes under hypoxic conditions. Cardiomyocytes expressing shLacZ or shG0s2 (#2) were cultured under normoxic or hypoxic conditions for 18 h. (*E* and *F*) The OCR in cardiomyocytes expressing shLacZ and shG0s2 (#2) under basal conditions and in response to the indicated mitochondrial inhibitors ($n = 8$). FCCP, carbonyl cyanide-4-(trifluoromethoxy)-phenylhydrazone. Data are represented as the means ± SEMs. n.s., not significant. $^{**}P < 0.01$; $^{***}P < 0.001$.

studies of F_oF_1-ATP synthase have revealed that this enzyme has a specific structure that connects two molecular nanomotors that synchronize with each other to produce ATP (26–30). These physically distinct structures suggest that a specific activating factor for F_oF_1-ATP synthase must exist. Combined with the findings from this study, we hypothesize that G0s2 may lower the activation barrier of the F_oF_1-ATP synthase nanomotor and enhance the ATP production rate with the equivalent proton motive driving force (PMF; i.e., the sum of the membrane potential and the pH gradient). Activation barriers might be generated by various factors, such as friction between the stator and rotor of F_oF_1-ATP synthase, physical and electrical resistance to proton transport through the channel, and the existence of rotary blockers such as the bacterial ε-subunit and cyclophilin D (31). The increased ATP production rate caused by G0s2 overexpression observed in the MASC assay supports this hypothesis, because the PMF in the initial phase of this assay should be the same. If this hypothesis is true, even with reduced PMF, cells that express G0s2 should produce ATP faster than cells that express little or no G0s2. In fact, G0s2 overexpression attenuated the decline of $[ATP]_{mito}$ under hypoxic conditions that reduced the PMF. Precise real-time measurement of the PMF is currently difficult, but these hypotheses might be proven in future studies. Kinetically faster ATP production should accompany greater consumption of both O_2 and PMF; however, our results suggest that preserving ATP production is more beneficial than preserving PMF for cell viability, particularly when the O_2 supply is restricted but still exists. The transience of endogenous G0s2 expression induced by hypoxia might serve to protect tissues in the early phase of energy crisis. There may be specific mechanisms to decrease G0s2 expression under prolonged ischemia that have yet to be identified. Another possible mechanism by which G0s2 could increase the ATP production rate is that G0s2 increases the F_o-F_1 coupling efficiency of F_oF_1-ATP synthase. However, this hypothesis is less likely, because G0s2 altered the oxygen consumption rate to increase the ATP production rate. Although this uncoupling phenomenon has rarely been reported for mammalian mitochondrial F_oF_1-ATP synthase, we cannot completely eliminate the possibility that intrinsically

uncoupled F_oF_1-ATP synthase exists, because we could not accurately measure the amount of uncoupled F_oF_1-ATP synthase in intact cells.

G0s2 was first identified in cultured monocytes during the drug-induced cell cycle transition from G0 to G1 phase (18, 32). A limited number of studies have implied that G0s2 is involved in cell proliferation (33), differentiation (19), apoptosis (34), inflammation (35), and lipid metabolism (36) in various cellular settings. Moreover, G0s2 was reported to localize to the cytosol (33), endoplasmic reticulum (19), mitochondria (34), or the surface of lipid droplets (36). How G0s2 distinguishes these multiple functions is still not clear. In our hands, G0s2 is always localized to mitochondria, which was shown by immunostaining with two antibodies against different epitopes of G0s2 (Fig. S6). Complete depletion of mitochondrial staining by G0s2 knockdown strongly suggests the specific localization of G0s2 to mitochondria. We also showed that G0s2 specifically bound to mitochondrial F_oF_1-ATP synthase but not other OXPHOS protein complexes and functionally regulated OXPHOS activity. Together, these data suggest that G0s2 acts in the mitochondria. However, different cellular conditions may change the localization and role of G0s2. Additionally, G0s2-mediated changes in ATP metabolism may possibly affect the lipid metabolism or cellular proliferation. Additional studies will reveal the functional mechanisms by which G0s2 exerts these multiple functions in different cellular conditions.

In this study, we evaluated $[ATP]_{mito}$ and $[ATP]_{cyto}$ separately using FRET-based ATP biosensors in living cells. This dual evaluation revealed that $[ATP]_{mito}$ reflected mitochondrial ATP production with much greater sensitivity than $[ATP]_{cyto}$ (Fig. 1 and Movies S1 and S2). Because $[ATP]_{cyto}$ is strongly influenced by the activity of various cytosolic ATP hydrolytic enzymes and ATP buffering enzymes, $[ATP]_{cyto}$ does not always reflect the ATP availability that determines cellular function.

Taken together, our results indicate that G0s2 is a positive regulator of OXPHOS that works to increase the mitochondrial ATP production rate even under hypoxic conditions. Therefore, enhancing the level and function of G0s2 could be beneficial for hypoxia- and mitochondria-related disorders, such as ischemic diseases, metabolic diseases, and cancer.

Materials and Methods

Cells were infected with adenovirus encoding FRET-based ATP indicators AT1.03 or mit-AT1.03 to measure changes in cytosolic or mitochondrial ATP concentrations, respectively. Image acquisitions and FRET analyses were performed as described previously with some modifications (13). For the control of oxygen concentration during time-lapse imaging, digital gas mixer for stage-top incubator GM8000 (Tokai Hit) was used to create hypoxic (1% O_2) or normoxic (20% O_2) condition. Additional methods are found in *SI Materials and Methods*.

ACKNOWLEDGMENTS. We thank M. Murata for helpful discussions and advice, H. Miyagi (Olympus Co. Ltd.) for technical advice regarding microscopy, T. Miyazaki (Cyclex Co. Ltd.) for making antibodies, S. Ikezawa and A. Ogai for technical assistance, K. Tanaka for help with the purification of bovine F_oF_1-ATP synthase, and Y. Okada and H. Fujii for secretarial support. This research was supported by the Japan Society for the Promotion of Science through the Funding Program for Next Generation World-Leading Researchers (NEXT Program) initiated by the Council for Science and Technology Policy; grants-in-aid from the Ministry of Health, Labor, and Welfare–Japan; and grants-in-aid from the Ministry of Education, Culture, Sports, Science, and Technology–Japan. This research was also supported by grants from Takeda Science Foundation, Japan Heart Foundation, Japan Cardiovascular Research Foundation, Japan Intractable Diseases Research Foundation, Japan Foundation of Applied Enzymology, Japan Medical Association, Uehara Memorial Foundation, Mochida Memorial Foundation, Banyu Foundation, Naito Foundation, Inoue Foundation for Science, Osaka Medical Research foundation for Intractable Diseases, Ichiro Kanehara Foundation, and Showa Houkoukai.

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