Modular organization of cardiac energy metabolism: energy conversion, transfer and feedback regulation

R. Guzun,1,2 T. Kaambre,3 R. Bagur,1,4 A. Grichine,5 Y. Usson,4 M. Varikmaa,3 T. Anmann,3 K. Tepp,3 N. Timohtina,3 I. Shevchuk,3 V. Chekulayev,3 F. Boucher,2,4 P. Dos Santos,4 U. Schlattner,1 T. Wallimann,7 A. V. Kuznetsov,8 P. Dzeja,9 M. Aliev10 and V. Saks1

1 Laboratory of Fundamental and Applied Bioenergetics, INSERM U1055, Joseph Fourier University, Grenoble, France
2 Department of Rehabilitation and Physiology, University Hospital, Grenoble, France
3 Laboratory of Bioenergetics, National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
4 Experimental, Theoretical and Applied Cardio-Respiratory Physiology, Laboratory TIMC-IMAG, UMR5525, Joseph Fourier University, Grenoble, France
5 Life Science Imaging – In Vitro Platform, IAB CRI INSERM U823, Joseph Fourier University, Grenoble, France
6 University of Bordeaux Segalen, INSERM U1045, Bordeaux, France
7 Emeritus, Biology Department, ETH, Zurich, Switzerland
8 Cardiac Surgery Research Laboratory, Department of Heart Surgery, Innsbruck Medical University, Innsbruck, Austria
9 Division of Cardiovascular Diseases, Department of Medicine, Mayo Clinic, Rochester, MN, USA
10 Institute of Experimental Cardiology, Cardiology Research Center, Moscow, Russia

Abstract
To meet high cellular demands, the energy metabolism of cardiac muscles is organized by precise and coordinated functioning of intracellular energetic units (ICEUs). ICEUs represent structural and functional modules integrating multiple fluxes at sites of ATP generation in mitochondria and ATP utilization by myofibrillar, sarcoplasmic reticulum and sarcolemma ion-pump ATPases. The role of ICEUs is to enhance the efficiency of vectorial intracellular energy transfer and fine tuning of oxidative ATP synthesis maintaining stable metabolite levels to adjust to intracellular energy needs through the dynamic system of compartmentalized phosphoryl transfer networks. One of the key elements in regulation of energy flux distribution and feedback communication is the selective permeability of mitochondrial outer membrane (MOM) which represents a bottleneck in adenine nucleotide and other energy metabolite transfer and microcompartamentalization. Based on the experimental and theoretical (mathematical modelling) arguments, we describe regulation of mitochondrial ATP synthesis within ICEUs allowing heart workload to be linearly correlated with oxygen consumption ensuring conditions of metabolic stability, signal communication and synchronization. Particular attention was paid to the structure–function relationship in the development of ICEU, and the role of mitochondria interaction with cytoskeletal proteins, like tubulin, in the regulation of MOM permeability in response to energy metabolic signals providing regulation of mitochondrial respiration. Emphasis was given to the importance of creatine metabolism for the cardiac energy homoeostasis.

Keywords cardiac metabolism, creatine kinase, mitochondria, respiration regulation.

© 2014 Scandinavian Physiological Society. Published by John Wiley & Sons Ltd, doi: 10.1111/apha.12287
The mechanisms underlying the regulation of cardiac energy metabolism continues to be controversial (Saks et al. 2006a,b,c, Balaban 2009). The concept involves maintenance of energy metabolism homoeostasis and stable levels of intracellular concentrations of ATP, ADP and phosphocreatine (PCr) during cardiac cycles (Williamson 1979, Balaban et al. 1986, Saks et al. 2006a,b,c). Stability of intracellular PCr, ATP and ADP levels during wide range of heart workload and respiration rate changes (Balaban et al. 1986, Balaban 2009) suggests that efficient energetic signal communication systems operate within ICEUs between ATP consumption and ATP synthesis sites with minimal concentration changes and gradient (Dzeja & Terzic 2003, Saks et al. 2006a,b,c).

The review aims to describe advances in understanding of regulation of mitochondrial ATP synthesis within ICEUs permitting heart workload to be linearly correlated with oxygen consumption and ATP synthesis under conditions of metabolic stability.

**Structural basis of modular organization of cardiac energy metabolism. Adenine nucleotides compartmentalization and restricted intracellular diffusion**

Mitochondrial organization, dynamics and interactions with cytoskeleton govern regulation of energy metabolism (Hudder et al. 2003). In adult cardiomyocytes, intermyofibrillar mitochondria are localized at the A-band level of sarcomeres and are at Z-lines separated from each other by T-tubuls in close connection, to the SR (Katz 1992, Hayashi et al. 2009). Figure 1 shows an adult primary cardiomyocyte with...
individual mitochondria localized at the A-band. The immunofluorescent labelling of α-actinin (red colour) was used to mark sarcomeric Z-lines (Gonzalez-Granillo et al. 2012). Estimation of mitochondrial centre distribution by probability density function demonstrated that in cardiomyocytes individual intermyofibrillar mitochondria are regularly arranged according to ‘crystal-like’ pattern (Vendelin et al. 2005). T-tubules, oriented longitudinally along myofibrils and transversely at the level of Z-line, potentially may supply each mitochondrion with oxygen (Soeller & Cannell 1999).


Embedment of mitochondria into the cytoskeleton, their intimate localization relative to other membranous elements and enzymatic associations with structural proteins create mechanical barriers for diffusion of various metabolites, forming intracellular microcompartments (Saks et al. 1995). Kinetic analysis of respiration regulation by ADP revealed the dependence of the apparent affinity of mitochondrial respiration for ADP on cells structure. The apparent Michaelis constant for ADP (app. \(K_m\)ADP), which inversely represents the apparent affinity of respiration for ADP, is of about 370.8 ± 30.6 \(\mu\)M in permeabilized adult cardiomyocytes and about 7.9 ± 1.6 \(\mu\)M in isolated heart mitochondria (the Michaelis–Menten representation of ADP-stimulated respiration can be seen in Fig. 8b, Saks et al. 2012). Trypsin proteolysis of cardiomyocytes decreased the apparent \(K_m\) for ADP up to the level characteristic for isolated heart mitochondria due to the disruption of orgelles interaction with cytoskeleton and mitochondria disorganization (Kuznetsov et al. 1996). The apparent affinity of mitochondrial respiration for ADP also strongly depends on its source. The respiration rate of permeabilized adult cardiomyocytes achieved maximum value (\(V_{max}\)) at <20 \(\mu\)M of endogenous ADP, while millimolar concentration of the exogenous ADP was needed to obtain the same effect (Saks et al. 2001). For this experiment, endogenous ADP was produced by intracellular ATPases during hydrolysis of exogenous ATP. Higher apparent affinity of respiration for endogenous ADP in permeabilized cardiomyocytes was explained by its direct channelling associated with the restricted diffusion and intracellular compartmentalization (Saks et al. 2001). This assumption was confirmed by the experiment using ADP-trapping system, consisting of pyruvate kinase (PK) and phosphoenolpyruvate (PEP),

![Figure 1](https://example.com/figure1.png)

**Figure 1** Mitochondria distribution in adult rat cardiomyocyte. (a) Individual mitochondria, visualized by green auto-fluorescence of flavoproteins, are localized at the A-band level of sarcomere. Immunofluorescent labelling of α-actinin (red colour) was used to mark sarcomeric Z-lines. (b) Fluorescence intensity plot shows peaks of mitochondrial flavoproteins intensities (dotted line) which correspond to regions of ‘zero’ intensity of α-actinin (solid line). Reproduced from Gonzalez-Granillo et al. (2012) with permission.

© 2014 Scandinavian Physiological Society. Published by John Wiley & Sons Ltd, doi: 10.1111/apha.12287
which competes with mitochondria for ADP (Gellerich & Saks 1982). The phosphoenolpyruvate–pyruvate kinase system completely suppressed the respiration stimulated by exogenous ADP and inhibited not more than by about 20% of respiration stimulated by endogenous ADP (Saks et al. 2001, 2003, 2008). Abraham et al. (2002) have been shown that the diffusion of ATP is also restricted in cardiac cells. Studying kinetics of phosphoryl exchange through the creatine kinase (CK) and adenylate kinase (AK) reactions by $^{31}$P magnetic resonance spectroscopy ($^{31}$P MRS), Nabuurs et al. (2010) demonstrated that in muscle cells, ATP and even more ADP are bound to slowly rotating macromolecules or cytoskeletal proteins and are only transiently present as free ATP or ADP in the cytosol. In vivo studies of ATP and PCr diffusion in rat skeletal muscles using $^{31}$P MRS confirmed diffusional anisotropy induced by subcellular barriers (de Graaf et al. 2000). These and other studies have contributed to the formulation of hypothesis about modular organization of cardiac energy metabolism assuming that mitochondria, consuming ADP and re-synthesising ATP, are integrated with adjacent ADP-producing sites (ATPases of myofibrils and ion pumps) by means of proteins associated to cytoskeleton which contribute to mitochondrial organisation and intracellular energy flux transfer (Saks et al. 2001).

**Compartmentalized energy transfer**

Two theories were proposed to explain how metabolites overcome intracellular diffusion limitations: the theory of vectorial ligand conduction proposed by Mitchell (1979), and flux transfer in non-equilibrium steady state (Goldbeter & Nicolis 1976, Dzeja & Terzic 2003, Qian 2006, De la Fuente et al. 2010, Ge & Qian 2013). According to these theories, compartmentalized metabolic processes are integrated by metabolic channelling via enzymatic complexes which can associate physically with cytoskeleton creating metabolic pathways (Ovâdi & Srere 2000, Huang et al. 2001). This kind of communication was named compartmentalized energy transfer flux (Saks & Ventura-Clapier 1994, Hudder et al. 2003, Ovâdi & Saks 2004, Saks et al. 2008). High-energy phosphoryl flux between ATP-consuming and ATP-generating sites is transmitted by the driving force created by local disequilibrium in sequential rapidly equilibrating reactions catalysed by highly compartmentalized CK and AK iso-enzymes (Bessman & Carpenter 1985, Wallimann et al. 1992, Saks et al. 1994, Zeleznikar et al. 1995, Tuckerman et al. 2002, Dzeja & Terzic 2003, Aliev et al. 2011). It is known that flux wave propagation along coupled and rapid equilibrating chemical and biological reaction proceed much faster than diffusion of reactants and is capable of operating with minimal or no concentration gradients (Goldbeter & Nicolis 1976, Mair & Müller 1996, Dzeja et al. 1998, Dzeja & Terzic 2003). This explains why changes in cellular adenine nucleotide, which are intermediates in tightly coupled reactions, are not observed even with marked increases in metabolic flux (Balaban et al. 1986, Zeleznikar et al. 1995, Saks et al. 2006a,b,c).

Significant new insights regarding dynamics of muscle bioenergetics have been obtained from in situ measurements of intracellular energy fluxes by $^{18}$O isotope-assisted $^{31}$P MRS developed by Nelson Goldberg at University of Minnesota and Dzeja group at Mayo Clinic, Rochester, MN (Zeleznikar et al. 1995, Dzeja et al. 1998, Pucar et al. 2001, Dzeja & Terzic 2003). Cellular ATP hydrolysis in the presence of $^{18}$O-labelled water results in the incorporation of $^{18}$O into phosphoryl groups which movement through various phosphoryl transfer networks is detected by $^{31}$P MRS. Using this technique, authors demonstrated that in normal heart about 80–88% of the intracellular energy flux is carried by PCr through the CK reaction, about 15% via AK reaction and remaining 5–7% via glycolysis (Pucar et al. 2001, Dzeja et al. 2011a, Nemutlu et al. 2012).

Creatine kinase catalyses the reversible reaction of adenine nucleotides transphosphorylation, the forward reaction of PCr and MgADP synthesis and the reverse reaction of creatine (Cr) and MgATP production (Wallimann et al. 1992, 2007, 2011, Schlattner & Wallimann 2004, Schlattner et al. 2006). Mitochondrial CK (MtCK, sarcomeric and ubiquitous isoforms) is an octameric protein situated in the contact sites of two mitochondrial boundary membranes, neighbouring voltage-depending anion channel (VDAC) at the outer membrane and adenine nucleotide translocase (ANT) at the inner membrane. In the mitochondrial inner membrane (MIM), positively charged MtCK is bound to negatively charged cardiolipin. MtCK shares the same cardiolipin patches with ANT (Schlattner & Wallimann 2004, Schlattner et al. 2006, Wallimann et al. 2011). Due to this close localization, MtCK is functionally coupled to ANT and catalyses the transfer of phosphoryl groups from ATP generated by OxPhosph with PCr production. PCr is used by cytoplasmic isoform of CK (MMCK) localized in myofibrils at M- and I-band of sarcomeres and in SR (Wallimann & Eppenberger 1985, Kraft et al. 2000). MMCK rephosphorylates ADP released from active centre of myosin ATPase to ATP used within contraction cycle. MMCK is associated also with sarcosomal and SR membranes to regenerate continuously the local pools of ATP for membrane ATPases and for regulation of metabolic sensor – ATP-dependent K-channel in sarcolemma (Alekseev et al. 2012, Saks et al. 2001, 2002, 2008).
Thus, energetic communication between mitochondria and sites of ATP utilization proceeds through compartmentalized energy transfer mediated mostly by CK and also AK and glycolytic enzyme chains associated with mitochondria, myofibrils, nucleus and sarcolemma to provide energetic continuum throughout the cell. It also allows to avoid accumulation of MgADP close to ATPases. MgADP is an efficient competitive inhibitor of ATPases (myofibrillar, SERCA and sarcolemmal ion-pumps) and increased intracellular MgADP may reduce the rate of crossbridge detachment masking the length-dependent activation and Frank–Starling mechanism (Yamashita et al. 1994, Fukuda et al. 2000, Saks et al. 2006a,b,c). Due to the high affinity of MMCK for MgADP (app. \( K_m \) for ADP is about 10–35 \( \mu \)M), the ATP regeneration capacity of MMCK is very high preventing MgADP accumulation even when energy utilization exceeds energy production (Wallimann et al. 1992).

**Modular organization of cardiac energy metabolism into ICEUs**

Both, regularly arranged distinct mitochondria, integrated into a microdomain of energy producing/consuming cellular complexes, and compartmentalized energy phosphoryl transfer are met by the conditions of modular organisation of cardiac energy metabolism into ICEUs (Fig. 2). ICEU contains sites of ATP hydrolysis such as myofibrillar, SR, sarcolemmal, ion-pump ATPases which use mitochondrially synthesized ATP delivered through phosphotransfer networks (Fig. 2) (Saks et al. 1998, 2006a,b,c, 2007a,b, 2012, Kaasik et al. 2001). ICEUs are connected with each other; individual mitochondria or several adjacent mitochondria in cardiomyocytes can be taken to be in the centre of its own ICEU (Saks et al. 2009). Therefore, they may function as a coordinated network connected by messengers such as various metabolites or reactive oxygen species (Aon et al. 2003, 2007, O’Rourke et al. 2005, Liu & O’Rourke 2009, Aon & Cortassa 2012, Kembro et al. 2013). In spite of synchronized functioning, damage of one individual mitochondrion (e.g., depolarization by laser photoactivation) does not affect \( \Delta \Psi_m \) of neighbouring mitochondria or the total energy state of the sum of cardiomyocytes (Aon et al. 2003, 2007, Saks et al. 2012). ICEUs are integrated with calcium-induced calcium-release units, forming a system of intracellular compartmentalized calcium and energy transfer to support electromechanical coupling of cardiac muscle contraction. (O’Rourke et al. 2005, Bers & Despa 2006, Rizzuto & Pozzan 2006, Maack & O’Rourke 2007, Gunter & Sheu 2009, Hayashi et al. 2009, Liu & O’Rourke 2009, Saks et al. 2012, Kembro et al. 2013). The disruption of ICEUs due to the fusion of individual mitochondrion into one reticulum or fragmentation with formation of mitochondria clusters will defeat the integrated organization of cardiac energy metabolism altering mitochondrial energy conversion, intracellular distribution of energy fluxes and controlling signals as well as Ca\(^{2+}\) transients (Scorrano 2013, Varikmaa et al. 2014). Alterations in mitochondrial morphology, frequently associated with modifications of sarcomer structures and energy metabolism, have been implicated in different heart pathologies such as ischaemia-reperfusion and heart failure (Chen et al. 2009, 2012, Ong et al. 2010, Dorn 2013). Active mitochondrial fusion–fission dynamic have been seen in embryonic cardiac development and in cardiac differentiation of stem cells (Chung et al. 2013). However, fusion–fission cannot be excluded in perinuclear mitochondrial clusters and may occur between two contiguous intermyofibrillar mitochondria in adult cardiomyocytes (Kuznetsov et al. 2009).

Mitochondria, as proposed by Aon et al. (2007), Aon & Cortassa (2012), function as metabolic ‘hubs’ for multiple catabolic and anabolic pathways. Figure 2 schematically represents ICEU in which free fatty acids and carbohydrates are taken up by the cell and oxidized via the Krebs cycle to CO\(_2\), paralleled by the production of NADH and FADH\(_2\). These substrates are then oxidized in the respiratory chain reactions producing electrons to reduce O\(_2\) and pumping protons across the inner membrane to create the electrochemical potential. This potential is used by ATP synthase to regenerate ATP. Then, coupled mitochondrial CK catalyses the direct transphosphorylation of ATP to Cr, thus producing PCr. The ATPase reactions release the free energy of ATP hydrolysis to perform the cellular work. If workload increases, ATP production and respiration are increased due to the feedback regulation via the CK-system (Pucar et al. 2001, Ingwall & Weiss 2004, Ventura-Clapier et al. 2004, Ingwall 2006, Saks et al. 2006a,b,c, 2012). In the next part of this article, our interest will be focused in more detail on the mechanisms of this regulation.

**Regulation of mitochondrial respiration in permeabilized adult cardiomyocytes**

The role of MtCK-ANT functional coupling in respiration regulation in mitochondria in situ in permeabilized adult cardiomyocytes

The functional coupling of MtCK with ATP synthesis via ANT is a key element in the transfer of energy from mitochondrial ATP to PCr, which represents the basis for intracellular energy transport via CK/PCr shuttle (Wallimann et al. 1992, 2007, 2011,
Schlattner & Wallimann 2004, Schlattner et al. 2006). Comparative kinetic analysis of MtCK reaction in isolated heart mitochondria revealed that under conditions of activated OxPhosph, the MtCK reaction is strongly shifted to the direction of PCr synthesis using all mitochondrial ATP for PCr production (Saks et al. 1985, 2007a). The apparent constants of dissociation of MgATP from binary (MtCK.MgATP) and ternary (MtCK.Cr.MgATP) enzyme–substrate complexes (Kia and Ka, respectively, Fig. 3c) were decreased when OxPhosph of isolated heart mitochondria was activated (Table 1) (Jacobus & Saks 1982, Saks et al. 1985, 2007a). This decrease was explained by the direct transfer of ATP from ANT to MtCK due to their spatial proximity and functional coupling (Aliev & Saks 1993, Metelkin et al. 2006). A similar...
mechanism accounts for the reversed direct transfer of ADP produced by the MtCK reaction via ANT back to ATP synthase for rephosphorylation, as described later.

The apparent kinetics of MtCK in mitochondria in situ in permeabilized cardiomycocytes is totally different from that of in mitochondria in vitro (Table 1, Fig. 3a,c). The apparent constants of dissociation of MgATP from binary and, especially, ternary MtCK-substrate complexes are increased many times in mitochondria in situ in comparison to that in vitro (Guzun et al. 2009). This reflects the decrease in the apparent affinity of MtCK, situated behind mitochondrial outer membrane (MOM), for exogenous MgATP and indicates the enhanced restriction of exogenous MgATP diffusion at the level of MOM and within organized structures of ICEUs. The decrease in the apparent constants of dissociation of Cr from MtCK–substrate complexes suggests an increase in the apparent affinity of MtCK for Cr in situ.
Values were summarized from Jacobus and Saks (1982), Saks PCr, phosphocreatine.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Comparative kinetic analysis of mitochondrial creatine kinase in isolated mitochondria with and without activated oxidative phosphorylation (OxPhosph) and in situ in permeabilized cardiomyocytes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{in} \text{MgATP}$</td>
</tr>
<tr>
<td>Mitoch. in vitro – OxPhosph</td>
<td>0.92 ± 0.09</td>
</tr>
<tr>
<td>Mitoch. in vitro + OxPhosph</td>
<td>0.44 ± 0.08</td>
</tr>
<tr>
<td>Mitoch. in situ, perm. cardiomyocytes</td>
<td>1.94 ± 0.86</td>
</tr>
</tbody>
</table>

PCr, phosphocreatine.

Mitochondria in situ in comparison with in vitro (Table 1). The apparent constant of dissociation of PCr, however, did not change (Table 1). Increased affinity of MtCK for Cr and an unchanged affinity for PCr reveal their free diffusion through MOM in permeabilized cardiomyocytes (Guzun et al. 2009, Timo-hihina et al. 2009, Saks et al. 2012).

Measurement of phospho-metabolite concentrations (reflecting energy fluxes from mitochondria) in parallel with kinetic analysis of MtCK in permeabilized cardiomyocytes showed a continuous increase of PCr production in the presence of stable level of ATP (Fig. 3d) (Timo-hihina et al. 2009). The PCr production to oxygen consumption ($V_{PCr}/V_{O2}$) ratio was close to the theoretical ATP/O$_2$ ratio for cardiac cells in vivo. The $V_{PCr}/V_{O2}$ of Cr-stimulated respiration was about 5.7, while the theoretical efficiency of OxPhosph (P/O$_2$) is 6 (Timo-hihina et al. 2009). Thus, Cr is an efficient feedback regulator of respiration in permeabilized cardiomyocytes, as well as in skeletal oxidative m. soleus and mixed human m. vastus lateralis (Guzun & Saks 2010). Low apparent affinity of MtCK for Cr in these muscles (the apparent $K_{in} \text{Cr}$ is about 1.0–1.5 mM) shows that low concentrations of Cr are capable to significantly increase respiration rates up to the maximal rate of ADP-stimulated respiration (Guzun et al. 2011, Saks et al. 2012, Varikmaa et al. 2014).

The ADP recycling in functionally coupled MtCK reaction was studied in permeabilized cardiomyocytes using tools of Metabolic Control Analysis (Tepp et al. 2011). Metabolic Control Analysis allows quantitative determination of the degree of control that a given enzyme exerts on specific metabolic flux (Moreno-Sánchez et al. 2008). Control coefficient of ANT and ATP synthase on the energy flux increased when respiration was activated with substrates of the CK (Cr and ATP in the absence of extramitochondial ADP) in comparison with ADP-stimulated respiration (Tepp et al. 2011). The sum of flux control coefficients of the respiratory chain complexes, ATP synthase, inorganic phosphate carrier (PiC), MtCK and ANT larger than one can be explained by the local ADP recycling in coupled MtCK reaction and channelling of substrates through the macromolecular supercomplex (Kholodenko & Westerhoff 1993, Saks et al. 1996, Tepp et al. 2011).

Functional coupling of MtCK with ANT amplifies intramitochondrial adenine nucleotides turnover maintaining high rates of OxPhosph and coupled PCr production in the presence of Cr under conditions of limited MOM permeability enhancing adenine nucleotides microcompartamentalization (Saks et al. 2007a, 2012, 2014).

The role of mitochondria–cytoskeleton interactions in the regulation of mitochondrial respiration in situ in permeabilized cardiomyocytes

It is known that the selective permeability of VDAC depends on many factors, among them are the cell-specific pattern of VDAC isoforms; VDAC interaction with different proteins (tubulin, hexokinase II (HKII), macrotubule-associated proteins, plectin, desmin ...); cell-specific patterns of intracellular proteins capable to interact with VDAC and their functional state (polymerization state or post-translational modifications); biophysical properties of the channel itself, the kind of molecules passing through the channel and MOM phospholipid composition.

Several cytoskeletal proteins were tested for their ability to connect to MOM and control mitochondrial metabolism via controlling MOM permeability. For example, such a role has been suggested for desmin or for the 1b isotype of plectin that may interact with VDAC at MOM in cardiomyocyte mitochondria (Capetanaki 2002, Carré et al. 2002, Schröder et al. 2002, Capetanaki et al. 2007). Our attention was focussed on the β-tubulin cytoskeletal protein with its known structural, transport and metabolic functions (Sackett 2010). Using immunogold labelling of total β-tubulin, the presence of this protein at the...
mitochondrial surface in cardiomyocytes, between MOM and myofibrils, SR and sarcolemma membranes has been shown (Saetersdal et al. 1990), for example, a study of the distribution of β-tubulins by fluorescence confocal microscopy showed that βIII-tubulin is codistributed with mitochondria in adult cardiomyocytes and permeabilized myocardial fibres (Fig. 4) (Guzun et al. 2011, Gonzalez-Granillo et al. 2012, Saks et al. 2012). Hetero-dimeric αβ-tubulin may induce in vitro a reversible closure of purified VDAC protein reconstituted into lipid monolayers (Rostovtseva et al. 2008). Notably, the addition of heterodimeric αβ-tubulin to isolated heart mitochondria significantly increased the apparent $K_{\text{m}}$(ADP) up to the value characteristic to that of mitochondria in situ in permeabilized cardiomyocytes (Monge et al. 2008).

Tubulin can create a heterodimeric complex formed by two globular and two C-terminal tails (CTT) of α- and β-proteins. Globular α- and β-proteins can be polymerized into microtubules, while α- and β-CTT can interact with other intracellular structures and proteins. Truncated tubulin without CTT did not induce reversible blockage of purified VDAC typical for tubulin (Rostovtseva 2010). The CTTs of different α- and β-tubulin isotypes have almost similar length (from 10 to 20 aminoacid residues) and electronegative charges (from about –7 to –9) suggesting the possibility of reciprocal interaction with VDAC (Sackett 2010). Taking into account that anti-βII-tubulin antibody oriented against CTT finds its epitop and is visible in confocal fluorescent microscopy, we assumed that βIII-tubulin binds to the VDAC protein binding site situated on the cytosolic face according to Colombini functional conformation of VDAC, rather than penetrate into the VDAC channel (Colombini 2009, Rostovtseva 2010). The CTT of α-tubulin itself, however, can slip into the channel as it is described by Rostovtseva (Rostovtseva et al. 2008, Rostovtseva 2010). The role of α-tubulin isotypes in the regulation of mitochondrial metabolism is still not fully understood. Therefore, future studies of the intracellular distribution of α-tubulin isotypes could help to understand their function relative to VDAC and βIII-tubulin CTT binding. It is also conceivable that tubulin could increase VDAC affinity for other regulatory proteins that in our scheme are called ‘linker protein’.

Importantly, both colchicin treatment inducing microtubules depolymerization, and treatment with 0.8 m KCl used to remove myosin from cardiac muscle fibres (‘ghost’ fibres’), did not dissociate tubulin from its colocalization with mitochondria and did not change significantly the apparent affinity of respiration

---

**Figure 4** Confocal microscopy images of mitochondria [coimmunolabelled for voltage-depending anion channel (a, d), α-actinin (b) and βII-tubulin (e) arrangement in adult cardiac muscle fibres. Images (c, f) show that both mitochondria and βII-tubulin are arranged regularly between Z-lines. Scale bar 2 μm. Reproduced from Varikmaa et al. (2014) with permission.
for ADP. The apparent $K_m$($\text{ADP}$) of ‘ghost’ cardiac fibres was found to be close to intact permeabilized fibres and was about 280 $\mu$m (Guerrero et al. 2010). These findings indicate that the strong and intimate connection between MOM and tubulin is, most probably, due to the interaction with free dimeric tubulin. In adult cardiomyocytes, about 30% of tubulin is polymerized and 70% are in the heterodimeric state (Tagawa et al. 1998). These two conformational states of tubulin protein are in a dynamic balance driven by polymerization–depolymerization processes (Sackett 2010). Conversely, in cancer hepatoma cells, colchicine induces a decrease in the mitochondrial membrane potential (Maldonado et al. 2010). We assume that this essential difference with cardiac cells can be explained by the difference in regulation of energy metabolism. Intracellular energy transfer in hepatoma cells is directly carried out by ATP instead of PCR. This type of cells, as well as adult hepatocytes, does not contain MtCK (Fontaine et al. 1995). The restriction of ADP/ATP diffusion through VDAC, induced by depolymerized tubulin, is harmful for cells with mitochondrial OxPhosph stimulated notably by cytosolic ADP and missing (or insufficiently represented) alternative phosphoryl transfer networks (such as CK/PCr). Therefore, VDAC blockage, limiting ATP diffusion, results in the loss of mitochondrial membrane potential of hepatoma cells.

Differences in MOM permeability for ADP could also originate from the distinct expression patterns of VDAC isoforms. Striated muscles express three isoforms of VDAC (De Pinto et al. 2010). The decrease in the apparent affinity for ADP in permeabilized cardiac muscle fibres of VDAC1$^{-/-}$ mice and VDAC3$^{-/-}$ mice indicates the possible role of VDAC2 in the restriction of adenine nucleotides diffusion (Anflous et al. 2001, Anflous-Pharayra et al. 2007, 2011). VDAC2 isoform is mainly expressed in the heart of wild-type murins and its deletion is embryologically lethal (Anflous et al. 2001, Anflous-Pharayra et al. 2011). The interaction of microtubule-associated protein with VDAC2 (Lindén et al. 1989) reinforces our belief that $\beta$II-tubulin can bind to VDAC2 to regulate its permeability for adenine nucleotides. VDAC1 and VDAC3 are permeable to ATP/ADP, and this could be linked to the control by HKII (Anflous-Pharayra et al. 2007, Maldonado et al. 2010). VDAC1/3 null cells do not contain HKII bound to VDAC (Chiara et al. 2008). However, more studies are needed to address the specificity of VDAC interactions with proteins and to clarify mechanism of regulation of the VDAC-selective permeability using genetic manipulations by silencing $\beta$III-tubulin in adult cardiomyocytes or transfecting $\beta$II-tubulin into cells lacking this tubulin isotype.

Observations of adenine nucleotides microcompartmentalization and functional coupling of MtCK with ANT and limited MOM permeability for ADP demonstrate the important role of MtCK in the communication between mitochondria and intracellular energy-demanding processes (Dzeja & Terzic 2003, Saks et al. 2006b, Dzeja et al. 2011a).

To further investigate the role of MOM permeability in the regulation of respiration in situ, we analysed the effects of exogenous MgATP on respiration under different conditions (Fig. 5). Addition of ATP to permeabilized cardiomyocytes activates respiration due to production of endogenous ADP. The apparent $K_m$($\text{ATP}$) was found to be about 160 $\mu$m due to restriction of ADP diffusion in situ. In case of MtCK activation by the addition of Cr, the respiration rate increases rapidly due to continuous regeneration of ADP in intermembrane space (local cycling by activated MtCK reaction), thus decreasing the apparent $K_m$($\text{ATP}$) to 24 $\mu$m. Removal of extramitochondrial ADP by PEP-PK system (this system rephosphorylates ADP released from mitochondria to ATP) changes completely the kinetics of regulation of respiration controlled by MtCK by increasing the apparent $K_m$($\text{ATP}$) to 2 mM. Figure 5 shows that in situ high

Figure 5 Role of mitochondrial outer membrane permeability and ADP signalling in the regulation of respiration of permeabilized adult cardiomyocytes. (●) stepwise addition of MgATP activates respiration due to the production of endogenous extramitochondrial ADP. The apparent $K_m$($\text{ATP}$) is equal to $158 \pm 40.1$ $\mu$m because of the restriction of ADP diffusion in situ. (○) stepwise addition of MgATP in the presence of 20 mM of creatine increases rapidly respiration rates due to the stimulation by endogenous extra- and intramitochondrial ADP decreasing the apparent $K_m$($\text{ATP}$) to $24 \pm 0.8$ $\mu$m. (blue ▲) removal of extramitochondrial ADP by phosphoenolpyruvate–pyruvate kinase system mitochondrial creatine kinase increases significantly the apparent $K_m$($\text{ATP}$) to 2 mM because of restricted diffusion. Reproduced from Guzun et al. (2009) with permission.
amounts of extramitochondrial ADP cannot effectively stimulate respiration because of restricted diffusion. At the same time, small amounts of extramitochondrial ADP, which can play the signalling role, are necessary for maximum activation of respiration, but exclusively in case of active MtCK in the presence of Cr (Guzun et al. 2009, Saks et al. 2012).

The results of these studies highlight the important role of the ANT – MtCK – VDAC - Tubulin system in the regulation of respiration and energy-transferring fluxes in cardiac cells. This system creates a supramacromolecular complex which we called ‘Mitochondrial Interactosome’ (MI) (Timohhina et al. 2009, Saks et al. 2012). Specifically, it represents the ATP synthasome proposed by Pedersen (2007) and formed by ATP synthase, ANT and PiC, as well as MtCK that is functionally coupled to OxPhosph via ANT and with VDAC, which, in turn, interacts with certain regulatory (cytoskeletal) proteins (Fig. 6). MI can include also the respiratory supercomplexes (Chen et al. 2004). Along the cristae membranes, the MI contains only MtCK and ATP Synthasome. ATP produced by ATP synthase is transferred to MtCK due to its functional coupling with ATP synthasome, and then, MtCK transfers the phosphorl group from ATP to Cr. The final product, PCr, is then released from mitochondria as a main energy flux due to high selective permeability of VDAC. Recycled ADP is returned back to the matrix. However, VDAC is not completely impermeable for adenine nucleotides allowing small signalling amounts of ADP to reach ATP synthase. Regenerated ATP is transferred directly by ANT to MtCK which continuously recycles ADP and by doing so, maintains the production of the PCr energy flux. In this way, MtCK amplifies the cytosolic ADP signal and, due to its high selective permeability, VDAC separates mitochondrial energy PCr flux from cytosolic signalling.

**Formation of structure–function relationship in the development of ICEUs**

According to our previous studies, the formation of regular arrangement of mitochondria and cytoskeletal components in rat cardiac cells in developmental terms takes place in the course of 3 month, in parallel with the maturation of energy transfer systems of mitochondrial metabolism (Table 2, Fig. 7) (Tiivel et al. 2000). During the first neonatal days, mitochondria of rat cardiac cells are randomly clustered in the cytosol and situated mostly in the perinuclear area. At this developmental state, functional interactions between mitochondrial and cytoskeletal proteins, characteristic for adult cardiomyocytes, have not been formed yet, and therefore, no ICEUs have yet been established. In this stage of development, cardiac cells already use OxPhosph, but are relatively more dependent on anaerobic glycolysis (Lopaschuk & Jaswal 2010). Accordingly, at birth, the apparent $K_m(ADP)$ is relatively low ($75.0 \pm 4.5 \mu M$, cardiomyocytes from 3-day-old rat) compared with the adult heart and increases steadily to the adult levels ($317 \pm 29.5 \mu M$).

---

**Figure 6** ‘Mitochondrial Interactosome’ includes ATP synthasome formed by ATP synthase, adenine nucleotide translocase (ANT) and inorganic phosphate carrier (PiC), mitochondrial creatine kinase (MtCK) functionally coupled to ATP synthasome and voltage-dependent anion channel (VDAC) with regulatory proteins (βII-tubulin and other linker proteins). ATP regenerated by ATP synthase is transferred to MtCK due to its functional coupling with ATP synthasome. MtCK transfers the phosphate group from ATP to creatine. Produced PCr leaves mitochondria as a main energy flux due to high selective permeability of VDAC. Recycled ADP is returned to ATP synthasome via the functional coupling. Small signalling amounts of ADP can reach ATP synthase. Regenerated ATP is transferred directly to MtCK which recycles continuously the ADP maintaining production of the PCr energy flux. In this way, MtCK amplifies cytosolic ADP signal. Reproduced from Timohhina et al. (2009) with permission.

© 2014 Scandinavian Physiological Society. Published by John Wiley & Sons Ltd, doi: 10.1111/apha.12287
Table 2  Developmental changes in the values of maximal respiration rate ($V_{max}$) and the apparent $K_m$ for exogenous ADP [$K_m$(ADP)] measured in isolated from rat

<table>
<thead>
<tr>
<th>Days</th>
<th>App. $K_m$(ADP), μM</th>
<th>$V_{max}$, nmol min$^{-1}$ mg$^{-1}$ protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>75.0 ± 4.5*</td>
<td>44.9 ± 4.1***</td>
</tr>
<tr>
<td>14</td>
<td>81.9 ± 18.8***</td>
<td>70.5 ± 12.6*</td>
</tr>
<tr>
<td>21</td>
<td>138.4 ± 11.7**</td>
<td>110.3 ± 3.9</td>
</tr>
<tr>
<td>28</td>
<td>149.4 ± 8.1*</td>
<td>104.7 ± 4.7</td>
</tr>
<tr>
<td>60</td>
<td>185.3 ± 27.5*</td>
<td>109.8 ± 11.4</td>
</tr>
<tr>
<td>84</td>
<td>317.4 ± 29.5</td>
<td>104.6 ± 5.7</td>
</tr>
</tbody>
</table>

Ca\textsuperscript{2+}-tolerant cardiomyocytes were isolated by perfusion with collagenase as described previously (Tepp et al. 2011) (Table 2, Fig. 7). An up-regulation of MtCK expression and increase in its activity at second postnatal week is observed (Fig. 7b, Table 2). Western blot analysis shows the presence of MtCK at low level already after three postnatal days; they reach 60% of the adult level during second week (Fig. 7b). The effect of MtCK/Cr system on the mitochondrial respiration at postnatal day 3 is low and its activation takes place progressively from 14 to 84 postnatal days, when MtCK expression approaches the adult levels (Fig. 7b). Thus, CK-system is becoming progressively more capacitive in mediating the feedback regulation between ATP consumption in cytosol and production in mitochondria.

Summarizing, existing data indicate clearly that functional alterations in energetic metabolism during development can be associated with parallel changes in intracellular structural organization of mitochondria relative to myofibrils and cytoskeletal proteins. The studies of postnatal formation of ICEUs showed that the increase in apparent $K_m$(ADP) value and activation of CK/P\textsubscript{Cr} phosphoryl transpher system are interconnected and directly related to the time course of the visible appearance of mitochondria – βII-tubulin co-localization in the heart cells. These results indicate that functional interactions of mitochondria with cytoskeletal proteins could be important prerequisites for formation of highly regulated energy transfer network in adult cardiomyocytes. In conclusion, rat heart is structurally and metabolically mature at the age of 3 month, when ICEUs are fully formed and MtCK is active coupled to OxPhosph and forming microcompartmentalization for production of P\textsubscript{Cr} and efficient intracellular energy transport facilitated by the P\textsubscript{Cr}/Cr circuit shuttle.

Feedback signalling via near-equilibrium enzymatic phosphoryl transfer networks (regulation under working conditions)

Under physiological conditions, according to the Frank–Starling’s law, the force of heart contraction is regulated by ventricular filling and sarcomere length-dependent mechanism at constant metabolite concentrations and constant amplitude of Ca\textsuperscript{2+} transients (Fukuda & Granzier 2005, Saks et al. 2006a,b,c). The high degree of metabolic stability displayed by cardiac muscle comes from the high coordination between ATP utilization and regeneration. The regulation of mitochondrial ATP synthesis is governed by metabolic feedback through communicating of changes in compartmentalized Pi, ADP, AMP and Cr/P\textsubscript{Cr} ratios (Dzeja & Terzic 2003, Saks et al. 2006a,b,c, 2012, Aliev et al. 2011).

In several studies, the nature of the metabolic signalling within ICEU was studied using mathematical modelling of compartmentalized energy transfer based on experimental data (Aliev & Saks 1997, Dos Santos
et al. 2000, Aliev et al. 2011). The Aliev and Saks model considers the time-dependent diffusional exchange of ATP, ADP, PCr, Cr and Pi between myofibrils and intramyofibrillar mitochondria in cardiomyocytes. Mitochondrial OxPhosph is activated by ADP and Pi produced from ATP hydrolysis by myosin in the myofibril compartment. The model considers CK compartmentalization and the real non-equilibrium kinetics of the CK reactions in different cellular compartments (Aliev & Saks 1997, Dos Santos et al. 2000, Aliev et al. 2011). A detailed description of the last version of the model is given in the study described by Aliev et al. (2011).

According to this model, the cyclic ATP production in mitochondria during contractions is associated with cyclical oscillations of ADP and Pi concentrations in myofibrils. These data are confirmed by experiments in vivo using $^{31}$P MRS of isolated perfused heart. Fluctuations of PCr and Cr were in the order of 8–15% during the different phases of the cardiac cycle (Honda et al. 2002). Inorganic phosphate, Pi, is not consumed by the myofibrillar MMCK reaction and therefore diffuses freely and enters mitochondrial matrix via its carrier (PiC). Part of ADP is used by the myofibrillar MMCK reaction due to its non-equilibrium steady-state, and part of the ADP forms a gradient of concentration transmitted towards the matrix. The rephosphorylation of ADP in myofibrillar MMCK reaction increases the Cr/PCr ratio which is transferred towards MtCK via CK/PCr shuttle. The ADP signal reaches mitochondria and increases ATP regeneration. Regenerated ATP, due to MtCK–ANT functional coupling, supplies the MtCK reaction (which is also in non-equilibrium steady state) to produce PCr. As a result, the reactions catalysed by different isoforms of compartmentalized CK tend to maintain the intracellular metabolic stability (Saks et al. 1994, 2014, Dzeja & Terzic 2003, Schlattner & Wallimann 2004, Schlattner et al. 2006, Guzun et al. 2011).

Figure 8 shows the ADP dependence of rates of mitochondrial respiration and heart oxygen consumption under various conditions corresponding to different workloads (Fig. 8a) (Aliev & Saks 1997, Vendelin et al. 2000, Aliev et al. 2011). They are shown by coloured arrows and are confined to the area of physiological cytosolic ADP concentrations marked with a grey rectangle (Fig. 8b). When MOM is permeable, as in isolated mitochondria, the regulation of respiration by ADP is impossible because ADP concentrations are saturated even at the minimal workload and respiration therefore should be maximal. However, when ADP diffusion is restricted at the level of MOM, as in...
mitochondria in situ, the respiration rates become linearly dependent on ADP concentrations (Fig. 8b), and in fact, on heart workload, in accordance with the metabolic aspect of Frank-Starling law (Fig. 8c). The Frank–Starling law of the heart describes the ability of heart to change the force of contraction and stroke volume in response to changes in the end-diastolic volume (Opie 1998). The metabolic aspect of this law is expressed by linear dependence between the increase of left ventricular end-diastolic volume and the increase in respiration rates (Williamson et al. 1976) in the absence of detectable changes in the intracellular ATP and PCr content (Balaban et al. 1986). The linear dependence of oxygen consumption on [ADP], under physiological conditions, can be amplified by Cr in the presence of activated MtCK. So, this graph points to the importance of decreased MOM permeability in feedback regulation and restricted ADP diffusion in vivo (Fig. 8c).

It has been demonstrated that reduced function of CK-system and decreased energy flux is the most prominent energetic abnormality in human heart failure and myocardial infarction (Weiss et al. 2005, Neubauer 2007). Using technique of 31P MRS by saturation transfer and synchronisation with cardiac cycle ATP flux via the CK reaction was analysed in vivo (Weiss et al. 2005). Authors’ demonstrated that the ATP flux through CK reaction is reduced by 50% in patients with heart failure even under conditions of relatively small changes of PCr and ATP. In a recent paper, the same group demonstrated that overexpression of MtCK improves energy reserves of heart and

![Figure 8](image_url)
Cardiac intracellular energetic units • R Guzun et al.  Acta Physiol 2015, 213, 84–106

protects from toxic insults, for example, by doxorubicin cardiotoxicity (Gupta et al. 2013). Augmentation of cardiac MMCK expression attenuated ischaemic acidosis, reduced injury and improved not only high-energy phosphate content and the rate of CK ATP synthesis in post-ischaemic myocardium, but also recovery of contractile function (Akki et al. 2012).

Recently, Phillips et al. (2012) hypothesized that the mitochondrial ATP synthesis matching in cardiac cells intracellular ATP hydrolysis under conditions of metabolic homoeostasis is regulated by posttranslational modifications (PTMs) of OxPhosph complexes, specifically of F1F0ATPase. Authors demonstrated that the activity of F1F0ATPase isolated from pig heart is lower than that from liver. This inhibition was due to the phosphorylation of several enzyme subunits. Modulation of isolated F1F0ATPase activity by dephosphorylation, on the one hand, and the increase in F1F0ATPase activity in response to the dobutamin stress, on the other hand, allowed authors to conclude that persistent reversible PTMs regulate variable F1F0ATPase activity in response to metabolic stress (Phillips et al. 2012). This conclusion reinforced authors’ previous assumption. In Michaelis–Menten model of ATP production as a function of ADP concentrations, the rate of ATP production can be altered by changing the rate of the maximum ATP production at constant ADP concentration (Balaban 2012). Taking into account that the F1F0ATPase concentration is constant in the heart with workload, authors concluded that the change of maximum rate of ATP production can be achieved only by the modification of enzyme kinetics via PTMs (Balaban 2012, Phillips et al. 2012). However, this model of ADP-driven ATP production completed for isolated heart mitochondria (apparent $K_m$ for ADP is about 30 μM) does not take into account intracellular phosphoryl transfer networks participating to the signal transduction and amplification in highly organized heterogeneous intracellular medium. Aditionally, the F1F0ATPase dephosphorylation resulted from the incubation of isolated heart mitochondria in calcium-containing buffer (Phillips et al. 2012) allowed authors to link the hypothesis on PTMs regulation of OxPhosph with the hypothesis of parallel activation of excitation–contraction coupling and OxPhosph by calcium (Balaban 2002, 2012). The last hypothesis is reviewed by authors taking into account the results of OxPhosph regulation in mice knockdown for mitochondrial calcium uniporter (Pan et al. 2013).

Among other hypothesis, it was also proposed that the OxPhosph complexes PTMs have cardioprotective role due to the inhibition of enzyme hydrolytic activity which reduces the reverse ATP breakdown during ischaemia (Sun et al. 2007, Wang et al. 2013) and the protection by reversible PTMs of F1F0ATPase from permanent oxidative damage during ischaemia-reperfusion in spite of the expense of decreased ATP production (Sun et al. 2007, Sun & Murphy 2010, Murphy et al. 2012, Chung et al. 2013).

The role of creatine in cardiac energy metabolism

In spite of the long history based on the proof knowledge about the role of Cr in muscle cells respiration and important role of CK/PCr shuttle in energy transport in the heart and oxidative muscles, this topic continues to aliment scientific debates. Recently, it has been shown that mice, knockout for guanidine-acetic acid methyltransferase (GAMT/−−), which was associated with Cr deficiency, may have unaltered maximal exercise capacity and response to chronic myocardial infarction due to the metabolic flexibility (Lygate et al. 2013). Quite opposite results were obtained in arginine/glycine amino-transferase (AGAT) knockout and Cr-deficient mice in the same year by Nabuurs et al. (2013). Cr depletion leads to several metabolic abnormalities in skeletalmuscle, including reduced ATP, increased inorganic phosphate levels and reduced activities of proton-pumping respiratory chain enzymes and an elevated glycolytic contribution in ischaemic circumstances (Nabuurs et al. 2013). These changes were reversed by oral Cr administration. Cr treatment is effective in humans with AGAT deficiency too, preventing many neurological and functional abnormalities (Leuzzi 2002). The reason for the differences between results of these papers may lay in the method used for attainment of Cr deficiency and metabolic adaptations.

The AGAT knockout mouse, in contrast to the GAMT knockout one, does not synthesize guanidino acetic acid (GAA). The latter in the GAMT knockout skeletal muscle was shown to be phosphorylated by CK to form an alternative energy-rich phosphagen, phospho-GAA (PGAA), which still can be utilized as high-energy phosphagen, albeit at lower efficiency (Heerschap et al. 2007). Therefore, only AGAT knockout model can be regarded as real Cr-deficient model, while in GAMT knockout model, the functions of Cr/PCr pair are partially delegated to GAA/PGAA couple.

The question of efficiency of GAA/PGAA couple was explored by Kan et al. (2004). According to their data, in skeletal muscle during ischaemia, PGAA ‘was metabolically active in GAMT/−− mice and decreased at a rate comparable with the decrease of PCr in WT mice.’ In fact, the recovery rate of PGAA in GAMT/−− mice after ischaemia was reduced compared with PCr in WT mice. According to their data, the initial
recovery rate of PGAA in GAMT<sup>−/−</sup> mice hindleg muscles is 0.034 ± 0.003 mm s<sup>−1</sup> or about 3.44-fold lower than the rate of PCr restoration, 0.117 ± 0.01 mm s<sup>−1</sup>. However, this PGAA turnover rate can still support almost 80% of ATP turnover rate (0.043 ± 0.006 mm s<sup>−1</sup>) in GAMT<sup>−/−</sup> mice. These PCr and PGAA turnover rates are manifold times lower than the unidirectional exchange rates of phosphoryl transfer in the opposite direction, from PCr to ATP (9.7 ± 0.5 mm s<sup>−1</sup>) and PGAA to ATP (<0.5 mm s<sup>−1</sup>), detected in magnetization saturation transfer (MST) experiments. The reasons of these dramatic differences are not precisely settled (Kan et al. 2004) and 31P NMR saturation transfer data are undergoing reinterpretation (Balaban & Koretsky 2011, From & Ugurbil 2011, Kemp & Brindle 2012).

Of note is that MST experiments on mouse hearts knockout for GAMT still revealed about fivefold difference in PCr or PGAA signal intensity decrease upon 6 s saturation of [γ-P]-ATP peak (Lygate et al. 2013). Also in vivo in structurally organized and tightly coupled reactions the real kinetics may be very different from the classic kinetics of free enzymes in solution (Saks et al. 2007a,b).

Suppose, in accord with data of Kan et al. (2004), the real rate of PGAA restoration is 3.5-fold lower than that of PCr, and then, we can illustrate by modelling the main energetic consequences of PCr substitution in heart muscle by PGAA. The results of this modelling, presented in Appendix S1, indicate an impaired cardiac contractile function associated with possible slowing of CK reactions in PGAA substituted hearts. Such changes were really detected by Lygate et al. (2013).

There may be no differences in the response to chronic myocardial infarction observed between WT and GAMT knockout mice could be predicted. Since in acute ischemic insult phosphagens are rapidly depleted and hearts in that respect becoming almost equal. Interestingly, slowly metabolized phosphorylated Cr analogues cyclocreatine and β-guanidinopropionic acid (GP) can reduce ATP depletion and even prolong ischemic survival (Turner & Walker 1985, Oudman et al. 2013). In this regard, reduction of basal PCr by GP feeding in myocardial infarction hearts did not further impair mechanical function (Horn et al. 2001). Moreover, in hearts, hardly survived after severe myocardial infarction, pathological relations between main cellular systems may be too far from regulatory events in normal hearts. In this regard, homoarginine, another metabolite of AGAT, which has a role in NO generation and perhaps in energy metabolism too, was absent in AGAT<sup>(−/−)</sup> mice and increased in GAMT<sup>(−/−)</sup> mice (Choe et al. 2013). Cerebral damage and neurological deficits in experimental stroke were increased in AGAT(−/−) mice and attenuated by homoarginine supplementation (Choe et al. 2013), which is unlikely to occur without energetic and metabolic rearrangements. Interestingly, homoarginine levels have strong association with cardiovascular risk and mortality (Pilz et al. 2013). In conclusion, highly probable operation of GAA/PGAA couple, which can support significant part of ATP turnover, in GAMT knockout mice distinguishes this model from AGAT knockout model in which Cr is really absent without any functional substitution. These data, as well as data on CK knockout mice (van Deursen et al. 1993, Saupe et al. 1998, Bohm et al. 2000, Dzeja et al. 2004, 2011a,b), provide strong evidences for the important role of CK in the energy homoeostasis in muscle cells with high and fluctuating energy demands.

**Novel aspects and physiological relevance**

It is beyond doubt that understanding of how well is organized intracellular energetic infrastructure in cardiac muscle cells, how it is functioning, and how this organization is disappearing in case of pathology is important for medical science. This may open new frontiers in future for modern metabolic medicine and therapy for cardiac infarction or metabolic syndrome diseases when energy metabolism is pathologically altered. The use of microtubules depolymerizing agent, colchicine, has been demonstrated to be efficient in the treatment of post-operative atrial fibrillation (Imazio et al. 2011), the atrial fibrillation ablation therapy (Defteros et al. 2012) and prevention of secondary cardiovascular events in patients with stable coronary disease (Nidof et al. 2013, 2014). In all these studies, colchicine was used due to its anti-inflammatory effects, and no attention was paid to its potential implication in cardiac energy metabolism through microtubules depolymerization. In cancer cells (for example hepatoma cells), microtubules depolymerization by colchicine-induced depletion of mitochondrial membrane potential and cells death (Maldonado et al. 2010, Lemasters et al. 2012). This effect of colchicine is opposite to that observed in adult cardiomyocytes because of the cardinal difference in the structure/functional organization of energy metabolism. A large number of cancer cell-types, also non-beating NB HL1 cells, do not express isotype of βII-tubulin (Hiser et al. 2006) and mitochondrial isoform of CK (Patra et al. 2008). Therefore, it will be interesting to see if transfection of both proteins in cancerous NB HL1 cells could restore restored restricted ADP diffusion, microcompartmentalization and remodel them into cells with like-primary cardiomyocytes phenotype. One possibility for such
bioenergetic therapy is associated with reinforcement of the binding of tubulin to VDAC; in fact, this is may be capable to induce and maintain the regulation of mitochondrial respiration via microcompartmentalization of adenine nucleotides and the control of energy fluxes through external mitochondrial membrane.

Conflict of interest
None of the coauthors of this article have any conflict of interest.

This study was supported by Agence Nationale de la Recherche (SYBECAR project, nr RA0000C407), by INSERM, France, by Institutional Research Funding nr 23-1 from Estonian Research Council, by Russian Foundation for Basic Research [12-04-01267a] and by the Austrian Science Fund (FWF): [P 22080-B20].

References


Capetanaki, Y., Bloch, R.J., Kouloumenta, A., Mavroidis, M. & Psarras, S. 2007. Muscle intermediate filaments and...


Cardiac intracellular energetic units · R Guzun et al.

Acta Physiol 2015, 213, 84–106


Cardiac intracellular energetic units


Saks, V., Guerrero, K., Vendelin, M., Engelbrecht, J. & Seppet, E. 2006c. The creatine kinase isoenzymes in organized...


**Supporting Information**

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Model simulation of cyclic bursts of ADP concentration in myoplasm.

**Appendix S1.** Modeling of creatine deficiency.