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Phosphorylation of chicken brain-type creatine kinase affects a physiologically important kinetic parameter and gives rise to protein microheterogeneity in vivo

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In addition to the two monomer subunits of chicken brain-type creatine kinase (B-CK, EC, 2.7.3.2), termed Bb (basic) and Ba (acidic), another subspecies called Bb* was identified by chromatofocussing in the presence of 8 M urea (Quest et al., [20]). The latter low abundance protein species, isolated from tissue extracts, comigrated on 2D-gels with three minor species (Bb1-3), initially identified in immunoprecipitated, [^{35}S]methionine labeled in vitro translation products of cDNA coding for the basic monomer Bb. During in vitro translation experiments in the presence of [^{32}P]-γ-ATP, Bb1-3 were labeled while phosphatase treatment eliminated these minor species. It is concluded that Bb* is identical to Bb1-3 and represents phosphorylated derivatives of Bb. B-CK dimer populations from different tissues were separated by ion-exchange chromatography and the K_m values of the resulting fractions were determined under phospho-creatine (CP)-limiting conditions. In fractions containing only Bb and Bb* two kinetically different enzyme species were detected (K_m values for CP = 1.6 mM and 0.8 mM), while fractions containing B-CK dimers composed of the major Ba and Bb monomers, but no Bb*, were homogeneous in this respect (K_m for CP = 1.6 mM). Phosphorylation of Bb to yield Bb* is concluded to reduce the K_m of B-CK dimers for CP by about 50%. This K_m shift is within the range of CP concentrations found in tissues expressing the B-CK isoform and may therefore be of physiological relevance.

Phosphorylation of creatine kinase; Regulation of creatine kinase activity; Intracellular ATP level; Energetics

1. INTRODUCTION

Creatine kinase (CK) belongs to a class of enzymes called phosphagen kinases, with representatives in phyla throughout the animal kingdom, which catalyze the reversible transfer of high-energy phosphate groups from ATP to guanidino compounds, termed phosphagens, and vice versa [1]. The direction of the reaction favoured by CK depends on substrate concentrations, pH, on the isoforms involved and their subcellular location. Both, cytosolic brain-type B-CK and muscle-type M-CK, as well as the mitochondrial isoenzymes (Mi-CK) readily catalyze the reaction from CP to ATP (the so-called 'reverse reaction' [2]) under in vitro assay conditions at the appropriate pH and substrate concentrations resembling the cytosolic milieu [3,4]. However, studies of mitochondrial respiration in rat heart and sea urchin sperm provide strong evidence that energy channeling from the mitochondria into the cytoplasm depends upon the preferential catalysis of the forward reaction by Mi-CK from ATP to CP [5,6].

Enzymes catalyzing reversible reactions are generally not considered as targets for regulatory control [7]. Clearly, however, constraints imposed upon the mitochondrial isoform of CK by its environment determine the direction of the phosphate-group-transfer reaction catalyzed [4–6]. This observation emphasizes that the performance of enzymes catalyzing reversible reactions may also be regulated. Subcellular compartmentation does not provide the only possibility for such a control. Recently, it has been demonstrated that enolase, an enzyme catalyzing a reversible step in the glycolytic pathway, is phosphorylated by protein kinase C (PKC) and that this posttranslational modification has inverse effects on both reaction directions [7]. Potentially, mechanisms controlling the performance of cytosolic CK isoenzymes together with mechanisms specifying their subcellular distribution could determine local intracellular ATP levels, for the latter nucleotide is not homogeneously distributed within cells, but rather exists in compartmentalized pools [8,9]. Microheterogeneity of ATP distribution throughout the cytosol, however, also can occur independent of compartmentation by membranes [10], possibly due to the

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Abbreviations: The term B-CK stands for the dimeric brain-type creatine kinase isoenzyme (enzymatically active form). Bb, Ba, Bb* and Bb1-3 represent different B-CK monomers

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non-uniform distribution of ATP-generating and ATP-consuming reactions [11]. On the other hand, ATP may fulfil multiple regulatory functions in a cell. For instance, it is an allosteric inhibitor of phosphofructokinase, a key enzyme in the glycolytic pathway [12]. Furthermore, it modulates potassium channel [13,14] as well as EGF receptor [15] activity. The latter examples are typically membrane-bound functions. For certain cell types, evidence exists that the ATP concentration in the immediate vicinity of the cell membrane may be lower than that in the bulk cytoplasm [11]. In this context B-CK, which has been found associated with synaptic vesicles [16,17] seemed of particular interest.

Chicken B-CK is particularly heterogeneous, as initially revealed by 2D-gel analysis [18]. The two major monomer species present, designated Ba- and Bb-CK [19], were shown to be distinct proteins [20] which are encoded by different mRNAs [21]. An additional species termed Bb* was also isolated, although its nature remained unresolved [20]. Some minor species identified in cDNA-derived in vitro translation products [22,23], termed Bb1, Bb2 and Bb3 [24], are shown here to be phosphoproteins, which comigrate with Bb*.

We thus addressed the question whether post-translational modification of B-CK might influence the enzymes' kinetic properties under CP-limiting conditions, for limitation of CP seems to be an important parameter for the CK reaction and for brain energetics in general (see Discussion).

Evidence is provided that the presence of Bb*, which can be partially enriched by chromatofocussing [20], is responsible for the kinetic heterogeneity observed, with respect to the K_m for CP, in those fractions of native, dimeric B-CK, containing Bb* monomers. It is concluded that chicken Bb-CK is phosphorylated and that this modification induces a 50% decrease in the K_m value of the enzyme for CP.

2. MATERIALS AND METHODS

2.1. *B-CK purification*

Active B-CK dimers were purified as described [19]. The final separation of active dimer populations was achieved on an FPLC MonoQ anion exchange column (Pharmacia), while B-CK monomers were separated on an FPLC MonoP chromatofocussing column (Pharmacia) in the presence of 8 M urea [20].

2.2. *2D gel analysis*

Two-dimensional gel analysis was carried out according to O'Farrell with minor modifications as described [24]. After electrophoresis proteins in the gels were stained with Serva Blue G or transferred onto nitrocellulose [25] and reversibly stained for protein with Ponceau Red S. In comigration experiments with ^{35}S-labeled H4 Bb-CK cDNA-derived in vitro translation products [22,24], gels stained with Serva Blue G were subsequently prepared for fluorography using Amplify (Amersham). Protein positions were indicated on dry gels using radioactive ink arrows prior to exposure to X-ray films at −70°C.

2.3. *In vitro translation of B-CK mRNA*

Aliquots of frozen mRNA derived from in vitro transcription (kindly performed by T. Wirz) from a chicken Bb-CK cDNA full length clone [22] called H4 were in vitro translated in reticulocyte lysate (Promega) containing [^{35}S]methionine (Amersham) as described by the manufacturer, except for the addition of 40 U of RNasin (Promega) per 50 μl assay. The translated radioactive B-CK was immunoprecipitated by a specific rabbit anti-chicken B-CK antibody [16], the immune complexes collected on fixed *Staphylococcus aureus* (Ig-sorb) and the precipitated radioactive CKs were coelectrophoresed with biochemically purified protein on 2D gels. After developing the autoradiogram on X-ray film, the radioactively labeled B-CK was used as an internal standard for the identidication of B-CK subunit spots stained with Serva Blue G or by silver staining.

2.4. *Cotranslational phosphorylation assays*

Phosphorylation of B-CK was demonstrated by using a protein kinase activity residing in rabbit reticulocyte lysates (Soldati, unpublished). Synthetic transcripts of Bb-CK were translated as described above except for the absence of labeled [^{35}S]methionine, but including 100 μCi of [^{32}P]- γ-ATP. Unfortunately, it was not possible to use lysates depleted of ATP and CP by gel filtration through Sephadex G25 to achieve a higher specific radioactivity, for lysates treated in such a manner have been shown to be translation incompetent [26]. Therefore, untreated lysates had to be used for cotranslational phosphorylation and incorporation of ^{32}P yielded only very faint signals due to the high endogenous phosphate pools. Incubation was followed by immunoprecipitation [23,27] and extensive washing before preparation of the samples for 2D gel analysis.

2.5. *Treatment of purified B-CK fractions or in vitro translated Bb-CK with phosphatases*

Aliquots of translation reactions or purified Bb-CK, enriched in Bb* from MonoQ columns, were immunoprecipitated as described above. Immune complexes were collected with Protein-A or Protein-G Sepharose CL-4B beads (Pharmacia). The beads were then suspended in CIAP buffer (50 mM Tris-HCl, pH 8.0, containing 0.1 mM EDTA) and incubated in the presence of 50-100 U of calf intestinal alkaline phosphatase (CIAP, Pharmacia) at 30°C for 2 h [28]. The beads were then washed twice and the samples prepared for 2D gel analysis.

2.6. *Kinetic analysis of B-CK subspecies*

Creatine kinase activity was measured by pH-stat as described [3] and was expressed in IU (one international unit corresponds to 1 μmol of CP converted per min at pH 7.0 and 25°C). Individual fractions of the two B-CK peaks (type-I and type-II) obtained on MonoQ columns were subjected to kinetic analysis under CP-limiting conditions, but in the presence of excess ADP and Mg^{2+} (3 mM and 10 mM, respectively) (for details, see [3]). Aliquots of the same fractions were assayed for CK activity at different CP concentrations and the initial slopes (V) of the different curves recorded were compared to those obtained in the presence of excess (10 mM) CP (V_{max}). Results were linearized by plotting (V/V_{max}) versus ($V/V_{max} \cdot S$) (modified Eadie-Hofstee plots). The negative slopes of these curves are numerically corresponding to the K_m values for CP. Kinetically different species present in a mixture can be resolved by these plots. The K_m values were only considered statistically significant if at least four independent values of a plot could be used for regression analysis and if the correlation coefficient was 0.99 or higher. Statistical comparison of the regression coefficients (K_m) of single fractions was performed using the two-sided Student's t-test, the resulting error probabilities were indicated as P-values (P, see Table I).

3. RESULTS

3.1. *Bb* is a phosphorylated form of Bb-CK*

The basic main monomer (Bb), three minor species (Bb1, Bb2 and Bb3), the M12-Bb species, as well as a spot on the acidic side of M12-Bb (M12-Bb1) were

found as ^{35}S-labeled in vitro translation products using mRNA derived from the full length B-CK cDNA clone H4 (Fig. 1a). The M12-Bb species was shown recently to arise by alternative ribosomal initiation of the Bb-CK mRNA at methionine 12 [24]. Two minor species (Bb2 and Bb3) were also directly visible by protein staining in Fig. 1c, when purified B-CK protein was resolved on 2D gels using a higher voltage and different buffers during isoelectric focussing than before [20] (compare Fig. 2). The in vitro translation products themselves are not visible by protein staining methods. Phosphatase treatment of these products eliminated Bb1, Bb2 and Bb3, and the spot on the acidic side of the M12-Bb species (Fig. 1b). Only Bb (large arrowhead) and M12 (small arrow) remain after such treatment (Fig. 1b), indicating that the minor species, Bb1-3 and the more acidic M12-Bb1 satellite specified above, were the phosphorylation products of Bb- and M12-Bb-CK, respectively. This was confirmed in a complementary experiment by in vitro translation in the presence of [^{32}P]-γ-ATP. Under these conditions phosphorylation occurred and only the above specified Bb1,2,3- and M12-Bb1-CK minor monomer species were radioactively labeled (Fig. 1d).

An additional minor component, termed Bb*, was found enriched in the intermediate peak fractions during separation of subunits on the MonoP column in the presence of urea [20]. This component migrated to a position proximal to Bb indicated by an asterisk (Fig. 2), coinciding with that of the three minor species Bb1, Bb2 and Bb3 (Fig. 1). Using the identical method of 2D gel electrophoresis [19] these three minor species were not individually resolved (Fig. 2). Recent improvements of the 2D gel system for the purified protein indicate that Bb* contains all of these three minor species observed in vitro (Fig. 1c).

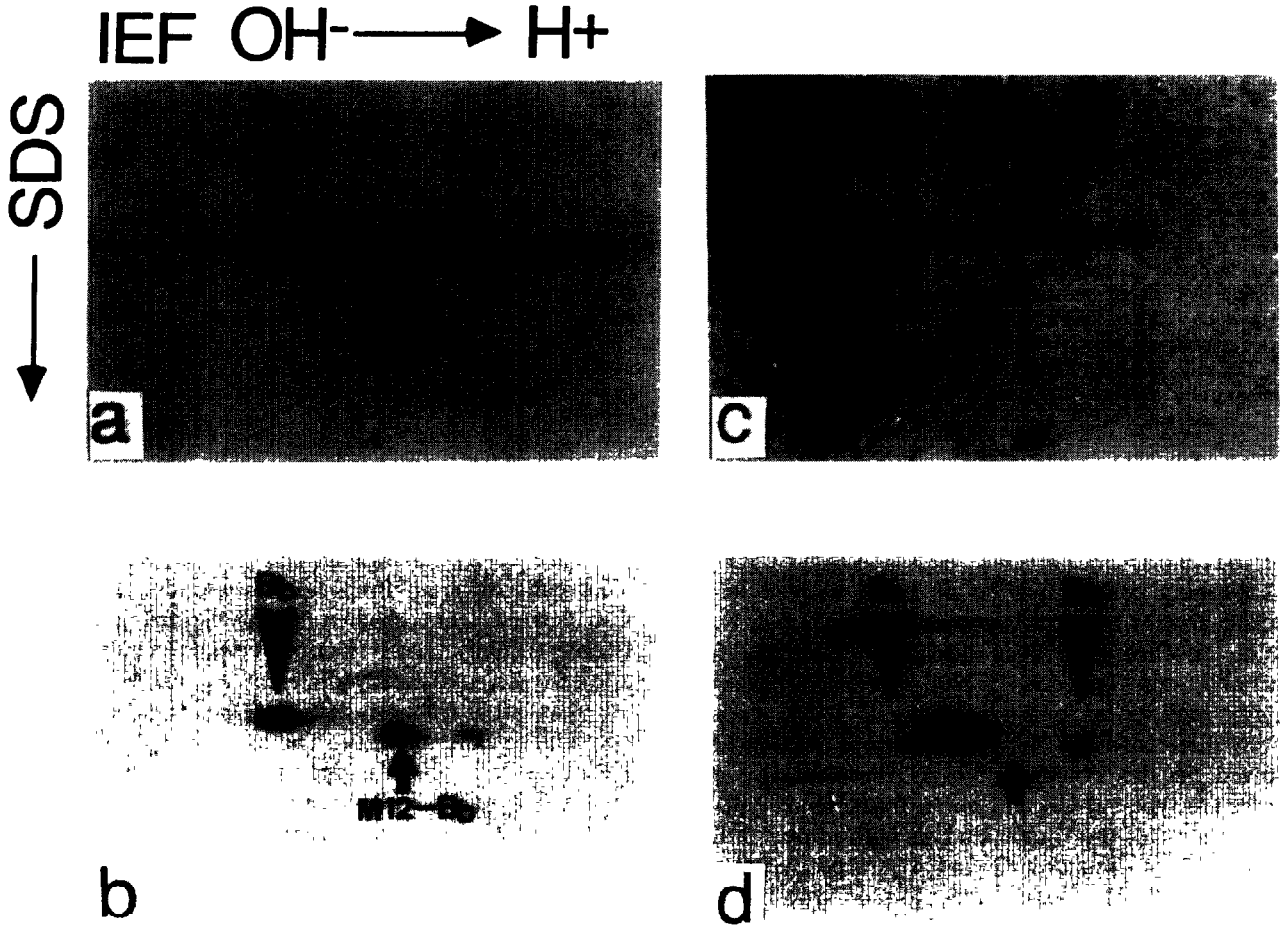

Fig. 1. Effect of phosphatase treatment on the migration behaviour of the Bb-CK protein subspecies and incorporation of radioactive phosphate into Bb-CK during in vitro translation. Immunoprecipitated in vitro translation products (reticulocyte lysate including [^{35}S]methionine) from mRNA derived from synthetic H4 B-CK cDNA were resolved on 2D gels and then transferred onto nitrocellulose. (a,b) Autoradiograms of blotted proteins before (a), and after (b) treatment with CIAP. (c) A sample translated in vitro in the presence of cold amino acids, but with [^{32}P]-γ-ATP after co-electrophoresis with 2 μg of purified B-CK, transfer onto nitrocellulose and protein staining with Ponceau Red S. (d) An autoradiogram of the sample analyzed in panel (c), stained for protein, shows incorporation of radioactive phosphate label into Bb1-, Bb2- and Bb3- as well as M12-Bb1-CK. Long arrowheads point to the main B-CK monomer species, Bb and Ba, whereas the short arrows indicate the position of the M12-Bb in vitro translation product arising from alternative initiation of translation at the methionine residue 12 [24].

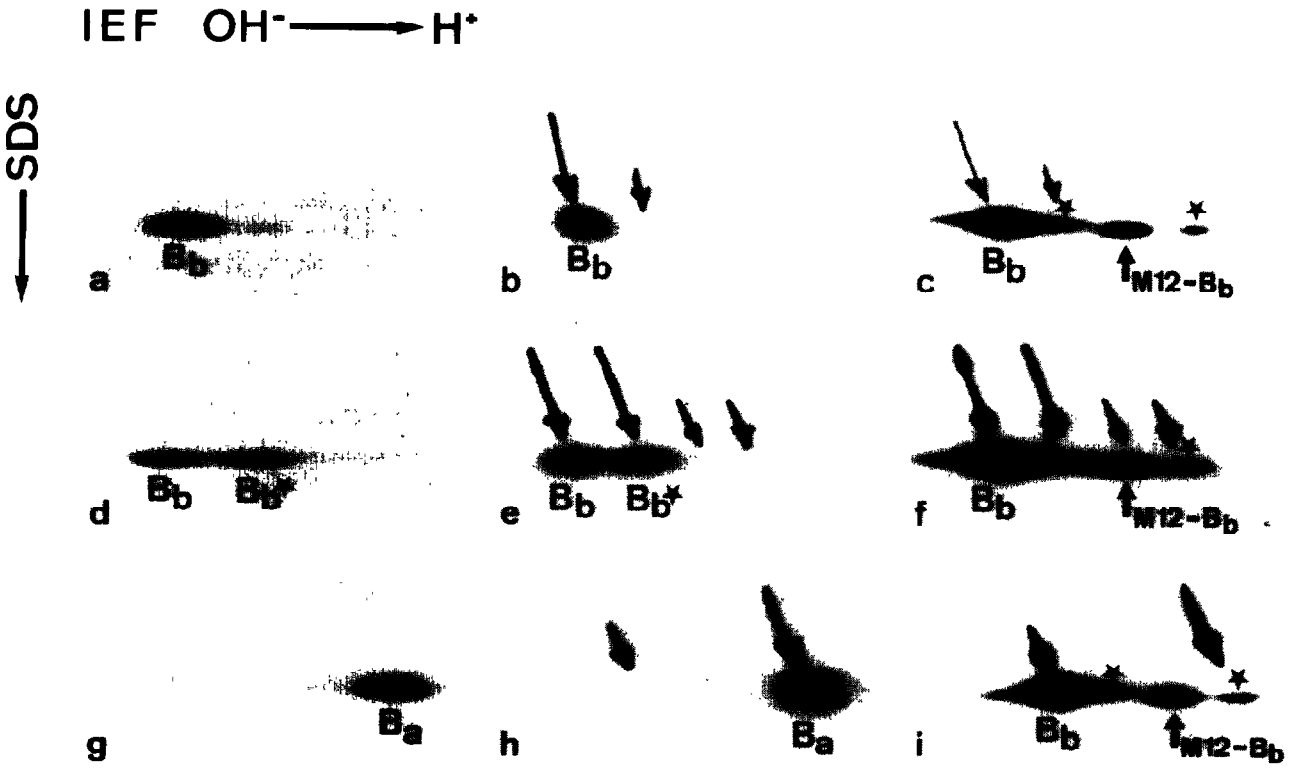

Fig. 2. Comigration of MonoP fractions of B-CK with in vitro translation products from a full length cDNA clone coding for Bb-CK. Samples from different fractions of a MonoP chromatofocussing column containing either Bb; Bb and Bb*; or Ba monomers, are shown in panels (a), (d), and (g) respectively, representing the corresponding 2D gels after staining for proteins with Serva Blue G. The samples were comigrated with H4 B-CK cDNA-derived, radioactively labeled in vitro translation products. (b), (e) and (h) show the same gels after soaking with Amplify, drying and marking visible protein spot positions with arrows of radioactive ink. Large and small arrows indicate positions of the major and minor protein species respectively, which were identified within the various fractions. (c), (f) and (i) show the autoradiograms on X-ray film of corresponding gels. The M12- Bb spot results from internal initiation (see Fig. 1). The spots marked by stars are phosphatase-sensitive in vitro phosphorylation products of Bb and M12-Bb (Fig. 1). Clearly, the enriched Bb* monomers migrate at the same position as the phosphatase-sensitive synthetic Bb1-3 species (compare Fig. 1).

3.2. *Phosphorylated Bb (Bb*) is responsible for kinetic diversity of B-CK dimer populations in different tissues*

A MonoQ column profile of B-CK derived from chicken gizzard extracts is shown in Fig. 3, panel A. Similar profiles have been discussed previously for heart and brain derived B-CK [20]. Two major peaks of activity, defined as type-I and type-II B-CK, representing different B-CK dimer populations are typically resolved on this column [19]. As representative examples for type-I B-CK and initial fractions of type-II B-CK, results of the kinetic analysis with respect to the K_m for CP of fractions 43 and 47, respectively, are shown in Fig. 3B. Clearly, the plots of type-I B-CK fractions were biphasic, while initial fractions of type-II B-CK were homogeneous in this respect. Since in these plots the negative slopes of the straight lines represent the K_m values for CP of the respective species, it is obvious that two distinctly different kinetic species were present in type-I B-CK fractions (Fig. 3B). Analysis of the corresponding fractions on 2D gels (Fig. 3C) show that, while type-II B-CK fractions contain both Ba and Bb monomers, only Bb and Bb* monomers are present in type-I fractions. The correlation between the presence of Bb* monomer and the existence of two kinetically different B-CK species was shown with B-CK derived from chicken brain, gizzard and heart (Table I). Only type-I fractions contained two kinetic species with statistically different K_m values for CP, whereas initial fractions of type-II peaks did not show this kinetic heterogeneity. The average K_m values for CP of the two species in type-I B-CK fractions were 0.8 mM and 1.6 mM, while in initial type-II fractions only the higher K_m value was found (Table I). These results show that phosphorylation product(s) of B-CK, similar to those found by in vitro phosphorylation experiments (Bb1,2, and 3, see Fig. 1), are also found in vivo (Bb*, see Fig. 2) and that B-CK dimers containing phosphorylated Bb-CK monomers (Bb*, see fig. 3C) display a distinctly different K_m for CP (see Fig. 3B). A low K_m value (0.8 ± 0.2 mM CP) was only found in fractions containing Bb* whereas the high K_m value (1.6 ± 0.3 mM CP) was found in all fractions (Table I).

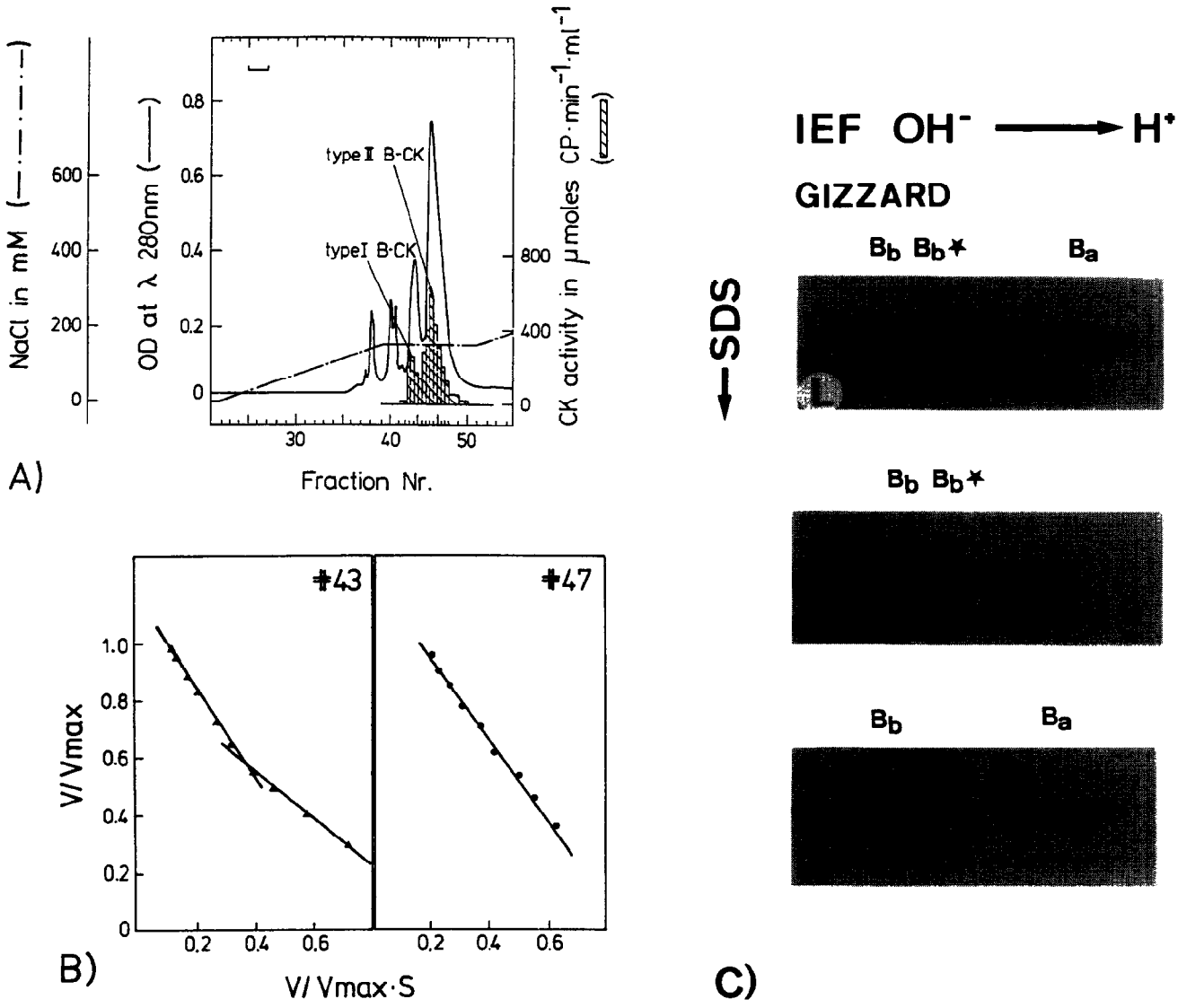

Fig. 3. Summary of the kinetic characterization of MonoQ peak fractions from gizzard extracts, yielding type-I and type-II B-CK. (A) A representative elution profile of gizzard B-CK on the MonoQ anion exchange chromatography column; absorbance at 280 nm (continuous line), salt concentration (dashed line) and CK-activity (shaded area) are shown. Fraction size varied; the bar length in the upper left hand corner represents an elution volume of 1 ml. (B) K_m analysis results are visualized by modified Eadie-Hofstee plots (whereby the negative slopes of the straight lines correspond to the K_m for CP, see section 1). In type-I B-CK fractions, represented here by fraction 43, two kinetically distinct species are present, whereas initial fractions of the type-II peak, represented here by fraction 47, appeared kinetically homogeneous. (C) 2D gel analysis of the B-CK-enriched pool loaded on the MonoQ column (L) reveals the presence of Bb, Bb* and Ba. In type-I B-CK fractions (43) only Bb and Bb* were present, while initial fractions of type-II B-CK (47) contained Ba and Bb monomers.

4. DISCUSSION

In previous experiments designed to resolve the nature of the two predominant chicken B-CK monomer species, Ba and Bb, an additional component Bb* was identified [20]. Its p*I* shift of about 0.1 unit of 2D gels with respect to Bb supported the hypothesis that this species may result from phosphorylation of Bb. Post-translational modification of brain-type CK was proposed to occur in rat brains [29], where this CK isoenzyme was shown to be phosphorylated by an unknown protein kinase present in crude brain microtubule preparations. However, the role of this modification, which to this point has not been studied in purified enzyme preparations, remained unclear.

In this paper, Bb* is shown to comigrate on 2D gels with those in vitro translated products of H4 mRNA, termed Bb1, Bb2 and Bb3, which are phosphatase-sensitive and can be labeled with [32P]-γ-ATP during in vitro translation experiments (for nomenclature of the different B-CK subspecies, see [24]). Therefore, Bb*, a B-CK component purified from tissue extracts, is iden-

Table I

Kinetic analysis of single Mono Q peak fractions of B-CK from chicken brain, gizzard and heart: comparison of K_m values

	Brain B-CK		Gizzard B-CK		Heart B-CK	
Fraction	43	47	43	47	22	25
Presence of Bb*	+	–	+	–	+	–
High K_m [mM]	1.42	1.51	1.57	1.40	1.75	1.57
Low K_m [mM]	0.71	–	0.83	–	0.55	–
$P <$	0.03	–	0.003	–	0.001	–
Average	high K_m value (mM CP) = 1.6 ± 0.3 ($n = 26$)					
	low K_m value (mm CP) = 0.8 ± 0.2 ($n = 23$)					

Representative set of K_m values for CP obtained for high K_m and low K_m B-CK species, measured for brain, gizzard and heart-derived enzyme, are summarized in the table. Initial type-II B-CK fractions (brain 47, gizzard 47, cardiac 25) containing essentially only Ba and Bb monomers in heterodimers, were compared with type-I fractions (43, 43 and 22, respectively), in which Bb and phosphorylated species thereof (Bb*) were present. The K_m value typically found for type-II B-CK was identical to the high K_m value found in type-I B-CK fractions (average 1.6 ± 0.3 mM CP, $n = 26$). Type-I fractions, containing the phosphorylated Bb* monomer species, exhibited a second kinetic species with a significant lower K_m (average 0.8 ± 0.2 mM CP, $n = 23$) compared to the high K_m value. If in the plots of single fractions two different slopes (K_m) were resolved (as for example in Fig. 3B, fraction 43), the statistical significance of this difference in K_m was analysed by using the two-sided Student's t-test; error probabilities are indicated by P-values. The resolution of B-CK dimers with lower K_m values correlated with the presence of phosphorylated Bb monomers (Bb*)

tical to the three Bb-CK-derived phosphoproteins observed in in vitro translation experiments. The regular spacing of the three Bb1-3 CK spots by approximately 0.05 pH units on 2D gels is indicative of multiple phosphorylation (e.g. Fig. 1d).

Initially, Bb* protein was not resolved into different subspecies. However, changes in isoelectric focussing conditions allowed the resolution of the Bb1-3 subspecies in purified B-CK (Fig. 1c), also supporting the conclusion that Bb* is identical to those three proteins derived from in vitro translation of H4 mRNA. The effects of phosphatase treatment on biochemically enriched Bb*-CK fractions characterized by 2D gel analysis (not shown) were considerably weaker than those observed from in vitro phosphorylated Bb1-3 CK species. Since the sensitivity of protein staining methods is much lower than that observed by fluorography of labeled proteins, higher amounts of proteins had to be used in those experiments, where biochemically purified protein was treated with phosphatases. Thus, the observation that the spots present within Bb*-CK were only partially removed, are most likely due to the lower phosphatase to protein ratio used as compared to those experiments where in vitro translated radioactive material was treated by phosphatases (Fig. 1).

In the final purification step of B-CK, typically two peaks of activity, type-I and type-II B-CK were resolved (Fig. 3A). Kinetic analysis of fractions from these peaks under CP-limiting conditions revealed the presence of two distinctly different kinetic species in type-I B-CK fractions, differing with respect to their K_m values for CP, while the initial fractions of the type-II B-CK peak were homogeneous in this respect. This observation was made with B-CK from several tissues (Table I), and the analysis of the corresponding fractions on 2D gels showed that only Bb and Bb* were present in the dimers of type-I B-CK fractions, while initial fractions of the type-II B-CK peak contained dimers composed of Ba and Bb, but no Bb* monomers. Therefore, it is concluded that the presence of Bb* monomers in dimers results in kinetic diversity of B-CK populations with respect to their K_m for CP.

Only initial type-II B-CK fractions were used in this kinetic comparison. Subsequent fractions may contain a wide variety of dimer species since at least 3 monomer components Bb, Bb* and Ba are present (Fig. 3C). At present, the possibility that Ba might also be phosphorylated cannot be excluded. Because the method of analysis used here can only accurately resolve two kinetically distinct species, the interpretation of kinetic data from type-II B-CK peak fractions becomes highly ambiguous. Since Bb* comigrated on 2D gels with several phosphorylated species derived from Bb-CK, it is concluded that it is the phosphorylation of Bb-CK that decreases the K_m of Bb-CK dimers from 1.6 to 0.8 mM with respect to CP. Both BbBb-CK dimers (present in type-I B-CK) and BaBb-CK dimers (present in type-II B-CK) appear to have the same high K_m values (1.6 mM CP). The observed reduction in the K_m from 1.6 to 0.8 mM CP lies within a physiologically relevant range of CP concentrations for tissues expressing B-CK. Rat and human brain, for instance, contain only 3 and 5 mmol of CP per kg of tissue, respectively [30,32], vs 30–40 mmol of CP per kg of rabbit skeletal muscle [31]. In addition, regional differences of CP content [32] as well as evidence for compartmentation of CP [33] and of CK

isoenzymes [34] were found in brain by non-invasive ^{31}P-NMR measurements and immunofluorescence staining, respectively. In the present work, the in vitro CK enzyme reaction was measured in the direction of ATP-synthesis, for in brain the physiologically relevant in vivo reaction of cytosolic B-CK is to guarantee the energy flux from CP to ATP, as shown directly by saturation transfer ^{31}P-NMR methods in intact human brain [32]. The importance of CP as a relevant physiological parameter is stressed by the fact, that the CP concentration of brain decreases during hypoxia or seizures without significant changes in ATP-levels [35]. Only if in addition the blood flow is decreased, CP and ATP levels fall towards zero rather quickly [36]. These data indicate that regional and possibly also subcellular fluctuations of CP levels can occur in brain. For these reasons, the effect of phosphorylation of brain-CK on the K_m value for CP described here is thought to be physiologically relevant.

In vitro phosphorylation, by PKC, of enolase, an enzyme catalyzing a reversible step in the glycolytic pathway, has inverse effects on both directions of the reaction; the forward reaction is enhanced, the backward reaction inhibited by this phosphorylation [7]. The results presented in this paper support the conclusion of the authors mentioned above that the activity of enzymes catalyzing reversible reactions can also be modulated by post-translational modification and that these enzymes, therefore, are also targets of regulatory control.

The mitochondrial CK isoform, bound to the outside of the inner mitochondrial membrane, operates essentially in one direction under physiological conditions, channeling energy-rich phosphate into the cytosol in the form of phosphocreatine [5,6,31]. Thus, it is reasonable to assume that subcellular localization, e.g. membrane association of B-CK isoforms [20,31,37] may additionally support or enhance the kinetic differences for the various B-CK dimer populations measured in solution. In this respect it is important to note that both cytosolic isoforms of CK, M- and B-CK, are also partially membrane-associated [16,17,37]. Recently, B-CK has been localized specifically at the plasma membrane of the outer segments of rod-shaped photoreceptor cells [37]. The regulation of CK activity by phosphorylation together with factors affecting intracellular partitioning (e.g. the association of CK with membranes which might be influenced by phosphorylation itself) may determine ATP levels at, and in the vicinity of, these membranes [31] and thereby directly modulate ATP-sensitive, membrane-associated functions [14,15,31, 37].

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