



Substrate profiling and aldehyde dismutase activity of the Kv β ₂ subunit of the mammalian Kv1 potassium channel

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ABSTRACT

Voltage-dependent potassium channels (Kv) are involved in various cellular signalling processes by governing the membrane potential of excitable cells. The cytosolic face of these α subunit-containing channels is associated with β subunits that can modulate channel responses. Surprisingly, the β subunit of the mammalian Kv1 channels, Kv β ₂, has a high level of sequence homology with the aldo–keto reductase (AKR) superfamily of proteins. Recent studies have shown that Kv β ₂ can catalyze the reduction of aldehydes and, most significantly, that channel function is modulated when Kv β ₂-bound NADPH is concomitantly oxidized. As a result, the redox chemistry of this subunit is crucial to understanding its role in K⁺ channel modulation. The present study has extended knowledge of the substrate profile of this subunit using a single turnover fluorimetric assay. Kv β ₂ was found to catalyse the reduction of aromatic aldehyde substrates such as 2, 3 and 4-nitrobenzaldehydes, 4-hydroxybenzaldehyde, pyridine 2-aldehyde and benzaldehyde. The presence of an electron withdrawing group at the position para to the aldehyde in aromatic compounds facilitated reduction. Aliphatic aldehydes proved to be poor substrates. We devised a simple HPLC-based assay to identify Kv β ₂ reaction products. Using this assay we showed, for the first time, that Kv β ₂ can catalyze a slow aldehyde dismutation reaction using 4-nitrobenzaldehyde as substrate and have identified the products of this reaction. The ability of Kv β ₂ to carry out both an aldehyde reduction and a dismutation reaction is discussed in the light of current thinking on the role of redox chemistry in channel modulation.

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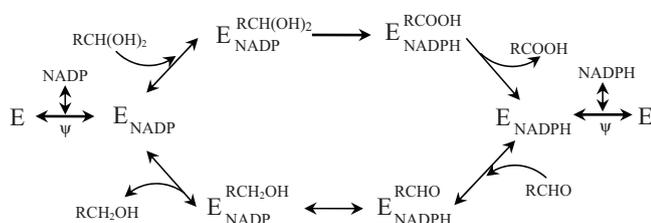
1. Introduction

Voltage-dependent potassium channels (Kv superfamily) play a key role in the mammalian nervous system by governing the resting membrane potential of excitable cells thereby modulating the frequency of action potentials and neurotransmitter release (Hille, 1991). Four voltage sensing, integral membrane pore-forming Kv α subunits assemble to form the Shaker-related voltage-gated K⁺ channels (Kv1 subfamily) (Kolb, 1990; Orlova et al., 2003). The auxiliary β -subunit, Kv β ₂, associated with the cytoplasmic face of Kv α proteins (Dolly et al., 1994; Parcej et al., 1992; Scott et al., 1994), has a conserved catalytic core that shows a high level of sequence homology with aldo–keto reductase (AKR) enzymes (Gulbis et al., 1999; Long et al., 2005). The catalytic C-terminal of Kv β ₂ has a tightly, but non-covalently, bound nicotinamide (NADPH) cofactor and an aldehyde binding site. Of all the variants of Kv β genes (Kv β _{1–3}), Kv β ₂ is the most widely distributed (Pongs et al., 1999; Xu and Li, 1998) and it strongly associates with several Kv α proteins.

Weng et al. (2006) showed that Kv β ₂ was catalytically active as an aldehyde reductase, identified substrates for this enzyme activity, and demonstrated modulation of channel function when Kv β ₂-bound cofactor (NADPH) became oxidized (Weng et al., 2006). This important finding focused attention on the redox properties of this channel subunit. It was suggested that oxidation of the bound NADPH induces a conformational change in Kv β , which propagates to Kv1.1 to effect channel inactivation (Pan et al., 2008a; Weng et al., 2006). Initially, two Kv β ₂ substrates were identified (4-cyanobenzaldehyde and 4-carboxybenzaldehyde) as being able to reversibly oxidize Kv β ₂-bound NADPH (Weng et al., 2006). Tipparaju et al. (2008) carried out a more detailed study of the Kv β ₂ substrate specificity using a multiple turnover reaction and showed that Kv β ₂ could catalyse the reduction of aldehydes and ketones with equal affinity.

Understanding the details of the redox chemistry of Kv β ₂ is essential for elucidating its mode of action. It has been suggested that it may respond to changes in the concentration of intracellular carbonyl substrates. Thus, an oxygen or metabolism-dependent change in carbonyl substrate concentration could rapidly alter the catalytic rate of Kv β ₂, leading to cofactor oxidation and to changes in Kv function (Tipparaju et al., 2008). The physiological

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Scheme 1. Kinetic mechanism of aldehyde dismutation proposed for Kvβ2 at pH 7.5. RCHO is an aldehyde, RCH(OH)₂ is its corresponding hydrate, RCH₂OH and RCOOH are the corresponding alcohol and carboxylic acid respectively. The dismutation of aldehyde substrate consists of two coupled half reactions. In the first half (the upper pathway), hydrated aldehyde is oxidized irreversibly to the corresponding carboxylic acid forming E_{NADPH}. In the second half reaction (lower pathway), another molecule of free aldehyde binds to the E_{NADPH} complex and is reduced reversibly to the corresponding alcohol. Hence, aldehyde is dismutated into equimolar concentration of corresponding alcohol and carboxylic acid in a redox silent reaction with no observable change in A₃₄₀. ψ denotes the cofactor exchange steps. The steps denoted by ψ are insignificant during dismutation as cofactor remains enzyme bound throughout alternate oxidation and reduction.

substrates responsible for the reduction/oxidation of the enzyme-bound cofactor are not known.

In addition to the well-characterized reversible oxidation of alcohols, a number of pyridine-linked dehydrogenases/reductases are known to catalyze the dismutation of aldehydes (Scheme 1) to equimolar concentrations of the corresponding alcohol and carboxylic acid (Daussmann et al., 1997; Henehan et al., 1995; Mee et al., 2005; Oppenheimer and Henehan, 1995; Steinbuchel and Schlegel, 1984; Winberg and McKinley-McKee, 1998). Kvβ2 bears some similarity to the microbial nicotinoprotein oxidoreductases in having a tightly bound, catalytically active NADPH cofactor (Schenkels et al., 2000). Since nicotinoprotein oxidoreductases function as aldehyde dismutases, it seemed possible that Kvβ2 might also catalyze aldehyde dismutation.

Herein, we extend the information on the substrate profile for this subunit in an attempt to identify compounds capable of interacting with Kvβ2. We identify the reduced reaction products for its optimum substrate, 4-nitrobenzaldehyde. In addition, the ability of Kvβ2 to catalyze an aldehyde dismutation reaction is established for 4-nitrobenzaldehyde and reduced and oxidized reaction products identified.

2. Materials and methods

2.1. Purification of Kvβ2

Kvβ2 gene from rat brain, cloned with an N-terminus His-tag as described in Dolly et al. (1994), was provided by Dr. Oleg Shamotienko. *Escherichia coli* BL21 (DE3, plysS) transformed with pET15b-Kvβ2 construct were cultured at 37 °C in LB medium containing 50 μg/ml ampicillin. When the A_{600nm} of the culture reached ~0.8, the expression of Kvβ2 protein was induced for 14 h by the addition of IPTG to a final concentration of 1 mM at 25 °C with constant shaking at 280 rpm (Stuart S1500 incubator/orbital shaker). Cells were resuspended in lysis buffer (20 mM Tris-HCl, pH 7.9, 5 mM imidazole, 200 mM NaCl) and lysed by sonication for 130 s on ice (VC-750 ultrasound generator, Sonics and Materials Inc.). Cell debris were collected by centrifugation and the supernatant applied to a nickel-charged iminodiacetic acid (Novagen) column pre-equilibrated with lysis buffer. The Ni²⁺ column was washed with 20 column volumes of the equilibration buffer before elution with 20 mM Tris-HCl, pH 7.9, 200 mM NaCl, and 300 mM imidazole. Fractions containing Kvβ2 were identified by SDS-polyacrylamide gel electrophoresis, pooled and dialyzed against 2 L of prechilled 0.2 M potassium phosphate, pH 7.5 for 36 h with three changes.

2.2. Fluorescence assay of the single step hydride transfer rate constant for Kvβ2 substrates

The rates of single turnover hydride transfer reaction were monitored using a Perkin Elmer fluorescence spectrometer LS50B at 22 °C. Assays were carried out in a quartz cuvette containing 2.0 μM Kvβ2 and varying substrate concentrations, in a final volume of 2.0 ml. All substrates were prepared in ethanol and then diluted into 0.2 M potassium phosphate buffer, pH 7.5 to the required concentration, keeping the content of ethanol in the reaction mixture equal to or below 1% (v/v). Ethanol at this concentration had no effect on enzyme-bound NADPH. The excitation wavelength used was 360 nm with a slit size of 15 nm and the emission spectra were acquired from 300 to 600 nm at different times after initiating the reaction by addition of substrate.

The decrease in emission at 454 nm due to enzyme-bound NADPH followed a single exponential function over time, which is consistent with the single-step hydride transfer reaction. Rate constants were estimated from the slope of a plot of ln [NADPH]_t versus time (t) and expressed as the inverse of the exponential time constant (see Fig. 3). The equation used was:

$$\ln F_t = -kt + \ln F_0$$

where F_t the fluorescence intensity at time 't', F₀ is the initial fluorescent intensity and 'k' is the rate constant. All assays were carried out in duplicate.

2.3. HPLC assay to monitor Kvβ2 catalysed dismutation of 4-nitrobenzaldehyde

Aldehyde dismutation was assayed in duplicate in 0.2 M potassium phosphate buffer, pH 7.5 containing 0.2 mM NADP⁺ at 37 °C in the presence of ~0.5 mg of Kvβ2 and 500 μM of 4-nitrobenzaldehyde (final vol. of 2.0 ml). The reaction was quenched by mixture with HPLC mobile phase (methanol/trifluoroacetic acid/water, 60:0.1:39.9) in the ratio 1:2. Aliquots (10 μl) of the resultant mixture were analysed on a Nucleosil C18 (3.9 × 150 mm) HPLC column, using a method adapted from Shearer et al. (1993) with monitoring by a Millipore Waters (Mississauga, Canada) liquid chromatography UV detector at 274 nm. Standard curves, constructed for 4-nitrobenzaldehyde, 4-nitrobenzyl alcohol and 4-nitrobenzoic acid were used to determine product concentrations in the reaction mixtures.

3. Results

3.1. Substrate screening studies by fluorimetric assay

Kvβ2, when purified, contains bound NADPH. During purification care must be taken to isolate the protein with the dissociable NADPH still bound. The presence of bound cofactor in recombinant Kvβ2-NADPH was observed by UV and fluorimetric analysis (Fig. 1). When excited at 360 nm Kvβ2 shows a prominent fluorescence peak at 454 nm corresponding to bound NADPH (Fig. 1 inset). After addition of substrate to freshly purified Kvβ2 in 0.2 M phosphate buffer, pH 7.5, the transfer of a hydride from the Kvβ2-bound NADPH to a substrate was observed as reduction in the 454 nm fluorescence peak (see Fig. 2A and B). This single turnover reaction allowed an investigation of the ability of Kvβ2 to catalyze the reduction of various aldehydes. This assay has previously been described for Kvβ1 (Pan et al., 2008a) and is more sensitive than the spectrophotometric assay first described for monitoring the reduction of aldehydes by Kvβ2 (Weng et al., 2006).

A continuous spectrophotometric assay has also been described for the aldehyde reducing activity of Kvβ2 (Tipparaju et al., 2008).

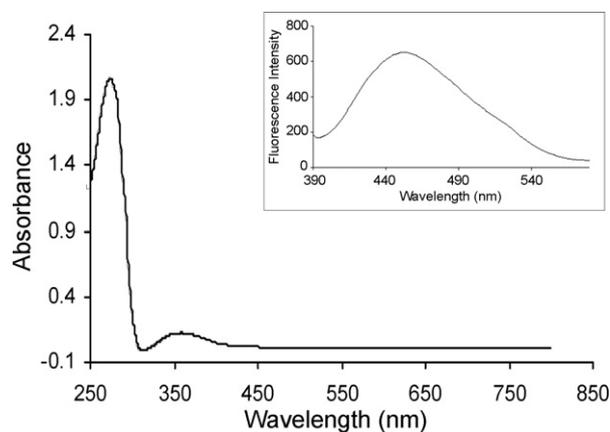


Fig. 1. UV/Vis and fluorescence spectra of freshly purified Kv β 2 protein. The UV spectrum of Kv β 2 gave two absorbance peaks at 280 nm and 360 nm corresponding to the protein and protein-bound NADPH, respectively (Liu et al., 2001; Schenkels et al., 2000). The inset is a fluorescence emission scan of purified Kv β 2 showing an emission band at 454 nm for bound NADPH. The excitation wavelength was 360 nm.

Such a multiple turnover assay is possible since the oxidized cofactor resulting from aldehyde reduction will exchange with externally added NADPH to recommence the catalytic cycle. In the present study, the multiple turnover assay was only used to identify the reduced product, 4-nitrobenzylalcohol derived from the reduction of 4-nitrobenzaldehyde. In our hands, multiple turnover initial rates measurements were complicated by slow bleaching of enzyme bound NADPH. Thus, multiple turnover initial rates were not used for kinetic constant estimations. The use of a single turnover reaction allows for the screening of a range of substrates. More detailed studies of kinetic constants were not pursued due to the low activity of Kv β 2 with the carbonyls tested as previously noted (Tipparaju et al., 2008).

When the initial rate of aldehyde reduction was measured by taking the slope of the linear part of the plot of fluorescence intensity at 454 nm versus time; the initial rate observed was linearly dependent on Kv β 2 concentration (Fig. 3).

3.2. Substrate profiling

Pseudo-first order rate constants were estimated for a range of aromatic and aliphatic aldehydes, ketones and dicarbonyls. All substrates were tested at a concentration of 0.5 mM except for certain aliphatic substrates that required a higher concentration to yield observable activity. A range of aldehydes of various struc-

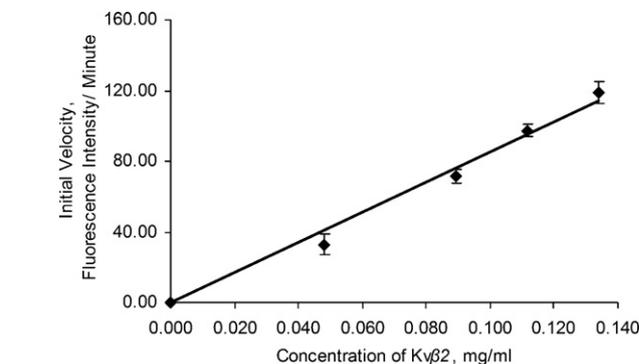


Fig. 3. Initial velocity of the hydride transfer reaction plotted versus Kv β 2 concentration for the single turnover reaction. The substrate (4-nitrobenzaldehyde) concentration was kept constant at 0.5 mM and initial velocities were measured by taking the slope of the linear part of the plot between fluorescence intensity and time. The concentration of enzyme employed was between 0.04 and 0.14 mg/ml.

tures were reduced by Kv β 2, with aromatic substrates bearing a strongly electron withdrawing substituent giving the largest rate constants (Table 1). Of these, 4-nitrobenzaldehyde gave the highest rate constant. All reactions were carried out at 22 °C due to the aggregation of Kv β 2 at higher temperatures. This assay is similar to that previously used to identify substrates for Kv β 1 (Pan et al., 2008a).

The effect of the position of the electron withdrawing group on the pseudo-first order rate constant was explored by comparing 2-nitrobenzaldehyde, 3-nitrobenzaldehyde and 4-nitrobenzaldehyde. It was found that the rate constants for these substrates decreased in the order: 4-nitrobenzaldehyde > 3-nitrobenzaldehyde > 2-nitrobenzaldehyde. All nitro-substituted benzaldehydes had higher rate constants than any of the other substrates tested. Thus, it was clear that the position of this group strongly influenced catalysis, with the para position being optimal. The single turnover rate constant for the hydride transfer reaction was estimated to be 0.22 min⁻¹ for 0.5 mM 4-nitrobenzaldehyde and assigned as 100%. Activities with all other substrates were expressed as a percentage of 4-nitrobenzaldehyde reductase activity reported for Kv β 2, had a rate constant (0.014 min⁻¹) more than 10-fold lower than 4-nitrobenzaldehyde. The rate constant with 4-cyanobenzaldehyde was similar to that for benzaldehyde showing that the nitro group significantly accelerated the Kv β 2-mediated aldehyde reduction. 2-Cyanobenzaldehyde had a rate constant half that of 4-cyanobenzaldehyde, supporting the observation that the position of the electron withdrawing group para to the aldehyde

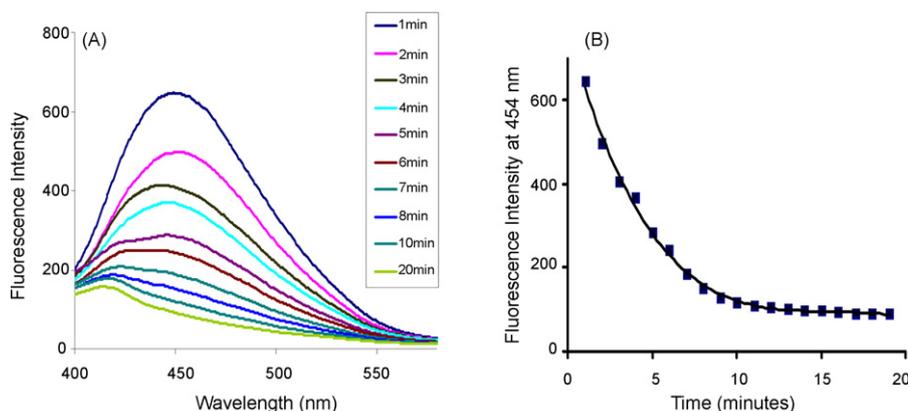


Fig. 2. Kv β 2 mediated reduction of 4-nitrobenzaldehyde. (A) Fluorescence emission spectra of purified Kv β 2 protein at different time points after mixing with 0.5 mM 4-nitrobenzaldehyde. (B) Fluorescence intensity at 454 nm plotted versus time for Kv β 2 after mixing with 4-nitrobenzaldehyde. This plot was fitted to a first order exponential decay to obtain a pseudo first order rate constant for aldehyde reduction.

Table 1Comparison of the rate constants (min^{-1}) for the single turnover hydride transfer reaction (first order) for Kv β 2 substrates.

Group	Substrate	Concentration of substrate (mM)	Rate constant (min^{-1})	Relative rate constant (%)
Aromatic aldehydes	4-Nitrobenzaldehyde	0.5	0.220	100 ^a
	3-Nitrobenzaldehyde	0.5	0.116	53
	2-Nitrobenzaldehyde	0.5	0.048	22
	Pyridine 2 aldehyde	0.5	0.011	5
	Benzaldehyde	0.5	0.017	8
	4-Hydroxybenzaldehyde	0.5	0.044	20
	2-Cyanobenzaldehyde	0.5	0.007	3
	4-Cyanobenzaldehyde	0.5	0.014	6
	4-Chlorobenzaldehyde	0.5	-	-
	4-Fluorobenzaldehyde	0.5	-	-
	Tolualdehyde	0.5	-	-
	Anisaldehyde	0.5	-	-
	Aliphatic aldehydes	Formaldehyde	10	-
2-Methylbutyraldehyde		10	0.035	16
Butanal		10	0.011	5
Crotanaldehyde		10	0.004	2
Valeraldehyde		10	0.002	1
Hexanal		0.5	0.001	1
Octanal		0.5	-	-
Succinic semialdehyde		20	0.012	5
Cinnamaldehyde		-	-	-
Ketones		Isatin	0.5	-
	4-Nitroacetophenone	0.5	0.004	2
Dicarbonyls	Methylglyoxal	10	0.015	7
	Phenylglyoxal	0.5	0.005	3

^a The single turnover hydride transfer rate for 4-nitrobenzaldehyde was 0.22 min^{-1} . Enzyme activity was measured as described in Section 2. Activities are expressed as percentage of 4-nitrobenzaldehyde reductase activity. All estimates of rate constants are the mean of triplicate measurements.

is important for optimal enzyme activity. This study indicates that a range of known AKR substrates may be reduced by this protein. Surprisingly, Kv β 2 showed no detectable activity with the aromatic aldehydes 4-chlorobenzaldehyde and 4-fluorobenzaldehyde.

Pyridine-2-aldehyde, a well-known AKR substrate, gave a rate constant of 0.011 min^{-1} . An aromatic alpha-keto aldehyde, phenylglyoxal, had a rate constant (0.0054 min^{-1}) about half that of the 4-cyanobenzaldehyde while an aliphatic alpha-keto aldehyde, methylglyoxal was a poorer substrate than both phenylglyoxal and 4-cyanobenzaldehyde. These data indicated the importance of activation of the aldehyde group for catalysis, and the importance of the aromatic moiety, presumably for binding.

4-Hydroxybenzaldehyde, with a moderately strong electron donating group in position para to the aldehyde was 5-fold less active than the 4-nitrobenzaldehyde but better than benzaldehyde. Aromatic aldehydes with moderate electron donating groups such as tolualdehyde and anisaldehyde showed no detectable activity. These data seem to indicate a complex picture of substrate preference. Nitrobenzaldehyde derivatives are clearly among the best aromatic substrates but other aromatic substrates, even those with electron withdrawing substituents such as chlorobenzaldehyde, showed no clear pattern of preference.

A para-substituted ketone, 4-nitroacetophenone, had an activity 50-fold less than 4-nitrobenzaldehyde indicating that Kv β 2 had rather poor affinity towards ketones. This finding contrasts with the conclusion of Tipparaju et al. (2008) who indicated that Kv β 2 could reduce aldehyde and ketone substrates with equal affinity. However, these workers noted that when presented with a choice between aldehyde and keto functional groups on a single substrate, 4-oxo-nonenol, only the aldehyde was reduced.

Aliphatic aldehydes are poor substrates with rate constants <100-fold or lower than aromatic aldehydes even at concentrations up to 10 mM. In this study, 2-methylbutyraldehyde was identified as a Kv β 2 substrate with a rate constant of ~10-fold higher than all other tested aliphatic aldehydes (Fig. 4). In mammals, isoleucine is one of three branched chain amino acids (leucine, isoleucine and

valine) that can cross the blood–brain barrier (Oldendorf, 1971a,b) where they serve as substrates for meeting parenchymal energy demand (Pellerin, 2005; Yudkoff et al., 1996). Formaldehyde, cinnamaldehyde and octanal showed no detectable activity with Kv β 2.

3.3. HPLC-based assay for the identification of reduced product of multiple turnover reaction using 4-nitrobenzaldehyde as substrate

Kv β 2-mediated formation of reduced product using a phospholipid aldehyde, 1-palmitoyl-2-oxoaleroyl phosphatidylcholine has been reported (Tipparaju et al., 2008). To date, 4-nitrobenzaldehyde is the most effective substrate for Kv β 2. Since this aldehyde has a high extinction coefficient, it was used as the basis for the development of a simple HPLC assay for aldehyde reduction/oxidation. The HPLC assay using this aldehyde proved to be a convenient and

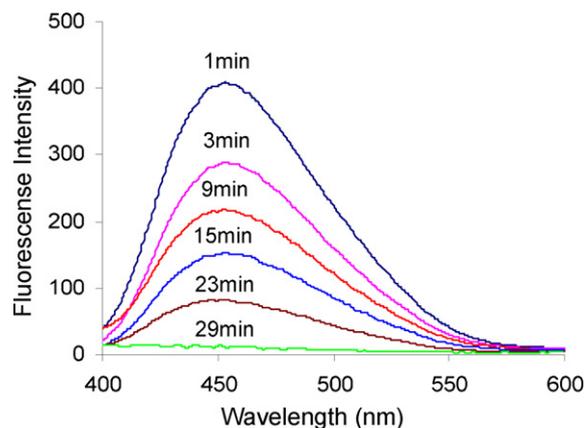


Fig. 4. Kv β 2 mediated reduction of 2-methylbutyraldehyde. Fluorescence emission spectra of purified Kv β 2 at different time points after mixing with 10 mM 2-methylbutyraldehyde which had a rate constant of ~10-fold higher than all other tested aliphatic aldehydes.

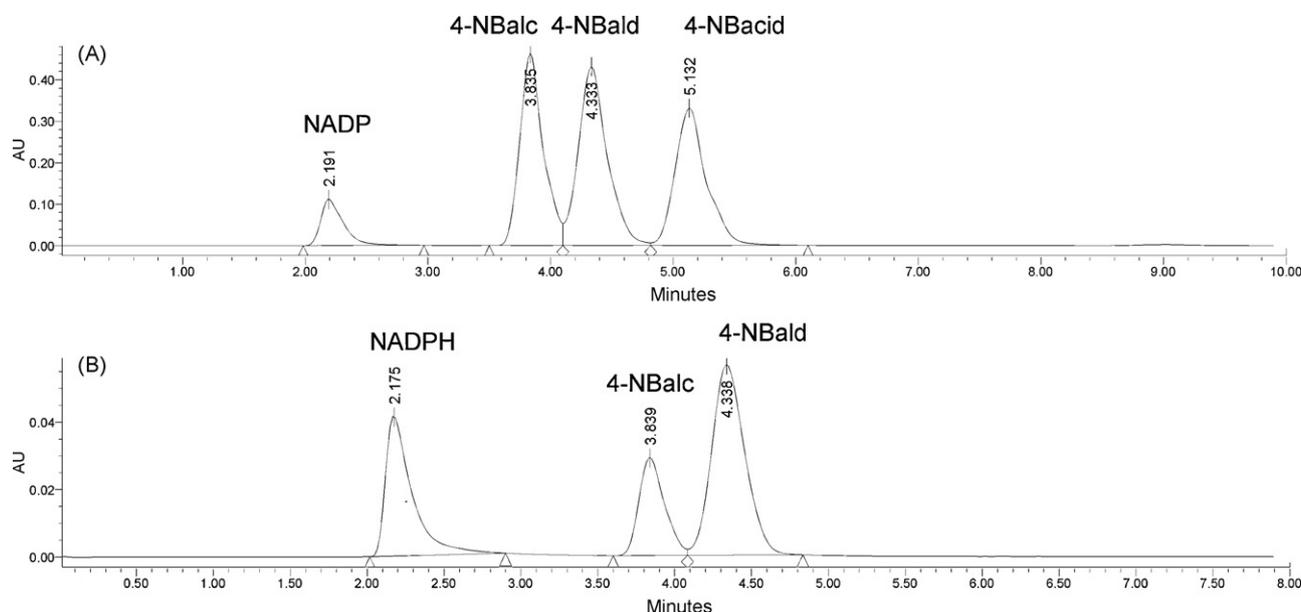


Fig. 5. (A) Standard HPLC profile of a mixture of equimolar (1 mM) concentrations of 4-nitrobenzylalcohol (4-NBalc), 4-nitrobenzaldehyde (4-NBald) and 4-nitrobenzoic acid (4-NBacid) containing 200 μ M of NADP; the retention times are 3.83, 4.33, 5.13 and 2.19 min, respectively. (B) Identification of products of Kv β 2 mediated multiple turnover aldehyde reduction reaction. The data show formation of 4-nitrobenzylalcohol (reduced product) with a retention time of 3.83 min in a reaction mixture containing \sim 10 μ M Kv β 2, 0.2 M potassium phosphate buffer (pH 7.5), 0.2 mM NADPH and 0.5 mM of 4-nitrobenzaldehyde. This mixture was incubated for 15 min at 37 $^{\circ}$ C. The peaks at 4.33 and 2.17 min represent unreacted 4-nitrobenzaldehyde and NADPH, respectively.

sensitive way to monitor aldehyde reduction and dismutation and will be broadly applicable to the assay of aldehyde dismutating enzymes. Separation of 4-nitrobenzaldehyde, and its corresponding alcohol and acid derivatives by HPLC is shown in Fig. 5A.

In the presence of externally added NADPH, Kv β 2 catalyses a multiple turnover reaction (see above). When the HPLC assay was used to monitor its reduction of 4-nitrobenzaldehyde, in the presence of NADPH, the formation of reduced product, i.e., 4-nitrobenzylalcohol (Fig. 5B) was clearly observed.

3.4. Dismutation of aldehydes by Kv β 2

A number of pyridine linked alcohol dehydrogenases/aldo-keto reductases have been reported to catalyse the dismutation of aldehydes (Daussmann et al., 1997; Henehan et al., 1995; Mee et al., 2005; Oppenheimer and Henehan, 1995; Steinbuchel and Schlegel, 1984; Winberg and McKinley-McKee, 1998). This reaction has previously been described for horse liver alcohol dehydrogenase;

hence, this enzyme was chosen to validate the assay conditions in this study (see below) (Oppenheimer and Henehan, 1995).

Purified Kv β 2.NADPH was first treated with 250 μ M 4-nitrobenzaldehyde to oxidize all enzyme bound cofactor before dialysis for 24 h against 0.2 M potassium phosphate buffer, pH 7.5 to remove remaining substrates. This step ensured that all Kv β 2 bound cofactor was in the oxidized form (Kv β 2.oxd). The reaction mixture containing \sim 10 μ M Kv β 2.oxd, 200 μ M of NADP, 0.2 M potassium phosphate buffer (pH 7.5) and 0.5 mM of 4-nitrobenzaldehyde was incubated at 37 $^{\circ}$ C. Aliquots were removed from the reaction mixture every hour and the products analysed by HPLC. This analysis revealed a clear peak for 4-nitrobenzoic acid (oxidized product) along with an equivalent amount of 4-nitrobenzylalcohol (reduced product) (see Fig. 6).

The HPLC based dismutation assay method was validated by using horse liver alcohol dehydrogenase (HLADH) and oxidized cofactor (NAD, 200 μ M) under the same conditions for which dismutation had been reported (Oppenheimer and Henehan, 1995)

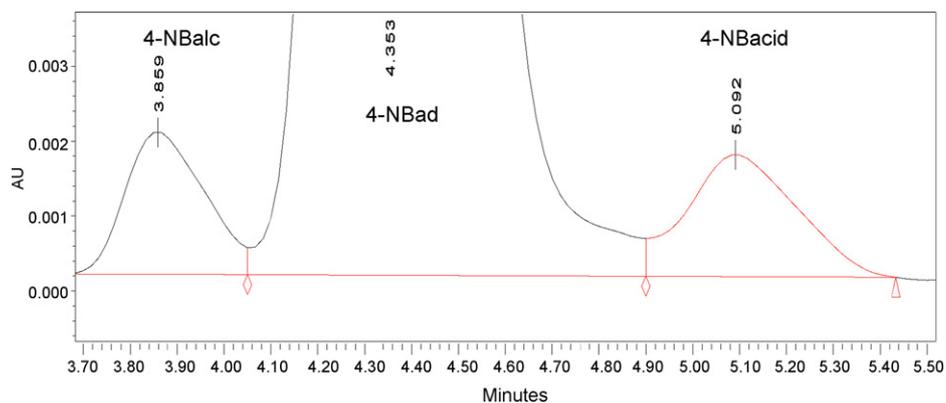


Fig. 6. Identification of the products of Kv β 2 mediated dismutation reaction. HPLC profile of the reaction mixture containing \sim 10 μ M Kv β 2.oxd, 0.2 M potassium phosphate buffer (pH 7.5), 0.2 mM NADP and 0.5 mM of 4-nitrobenzaldehyde incubated for 7 h at 37 $^{\circ}$ C showing the formation of 4-nitrobenzylalcohol (reduced product) along with an equimolar concentration of 4-nitrobenzoic acid (oxidized product, peak indicated in red) giving respective retention times of 3.85 and 5.09 min. The peaks at 4.35 represent unreacted 4-nitrobenzaldehyde. This experiment was repeated several times with identical results. Control experiments with no enzyme showed no alcohol or acid formation over the same time period.

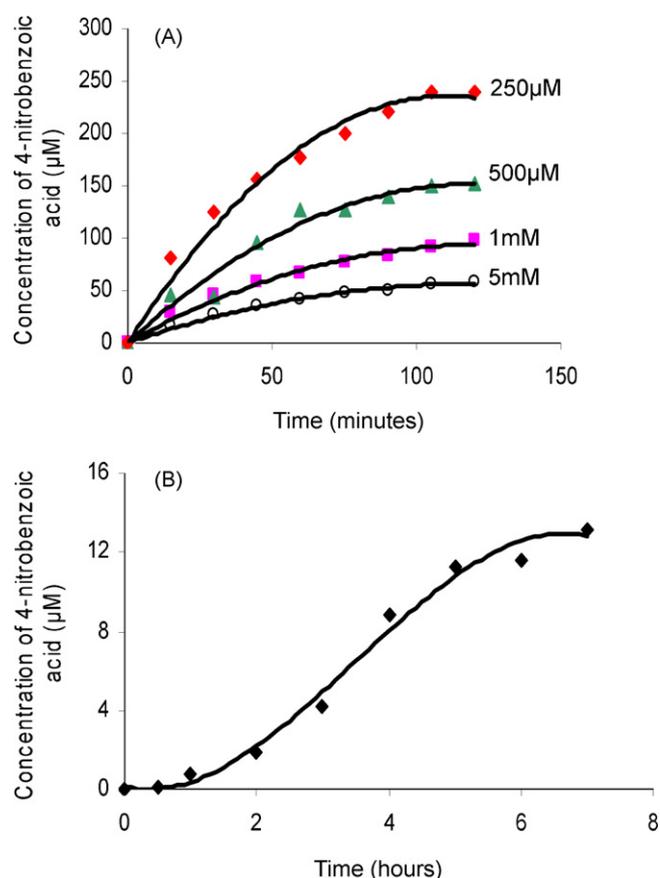


Fig. 7. (A) Progress curves showing 4-nitrobenzoic acid formation resulting from the dismutation of 4-nitrobenzaldehyde by horse liver alcohol dehydrogenase (HLADH). The data shows the formation of 4-nitrobenzoic acid at different starting concentrations of 4-nitrobenzaldehyde (250 μ M, 500 μ M, 1 mM and 5 mM). After addition of the HLADH to the assay mixture aliquots were removed at 15, 30, 45, 60, 75, 90, 105 and 120 min and the amount of 4-nitrobenzoic acid formed was estimated by HPLC. Results are expressed as the mean of duplicate measurements. The concentration of HLADH and NAD^+ used was 20 μ g/ml and 200 μ M, respectively, in a final reaction volume of 2 ml. (B) Dismutation of 4-nitrobenzaldehyde by Kv β 2. The data show the Kv β 2 mediated dismutation of 4-nitrobenzaldehyde with externally added NADP. After addition of substrate (500 μ M 4-nitrobenzaldehyde) to the assay mixture, aliquots were removed at 0.5, 1, 2, 3, 4, 5, 6 and 7 h and the amount of 4-nitrobenzoic acid formed was estimated by HPLC. Results are expressed as the mean of duplicate measurements. Assays were carried out as described in Section 2.

(see Fig. 7A). Dismutation may be conveniently monitored by following the accumulation of 4-nitrobenzoic acid, a reaction product unique to the dismutation reaction. Kv β 2 was shown to catalyze a slow dismutation reaction where the amount of 4-nitrobenzoic acid produced was found to be >1400 times less than HLADH in 2.0 h (see Fig. 7B).

Control reactions with no enzyme were incorporated in every experiment. Equimolar concentrations of 4-nitrobenzaldehyde, 4-nitrobenzoic acid, 4-nitrobenzyl alcohol and NADP^+ were incubated at 37 °C as a control to monitor any possible background chemical reactions. The data clearly showed that the products of the reaction observed were due to Kv β 2 catalyzed dismutation.

3.5. Comparison of Kv β 2-mediated multiple turnover and dismutation reactions

The amount of reduced product (4-nitrobenzylalcohol) formed from the multiple turnover reaction over the course of 30 min was \sim 30 times higher than that seen for the dismutation reaction. This was expected since dismutation involves the generation of Kv β 2-bound NADPH by the formation of 4-nitrobenzoic acid which is

presumably slow and expected to be rate limiting (Oppenheimer and Henehan, 1995).

4. Discussion

The substrate screening data in this study help to further define Kv β 2 substrate specificity and establish that Kv β 2 has a preference for aromatic aldehydes with strong electron withdrawing groups at a position para to the aldehyde moiety. It has been suggested that *in vivo* modulation of channel activity may be mediated by an aldehyde substrate. The identity of such a substrate is difficult to define when an enzyme has the broad specificity of Kv β 2. Most of the substrates we and others have examined are unlikely to be physiologically significant and physiological analogs are not easily identified. It has been suggested that this subunit is involved in the reduction of membrane-derived oxidized lipids (Tipparaju et al., 2008). However, it is difficult to envisage how the production of such aldehydes could be controlled sufficiently to regulate channel activity since they arise from a variety of processes (both enzymic and non-enzymic) mostly as a result of oxidative stress and would be expected to be competitive substrates.

The suggestion that aldehydes have a direct role in channel modulation (Tipparaju et al., 2008; Weng et al., 2006) presents some challenges. Firstly, most aldehydes are reactive species that readily react with, and modify, cellular proteins. Most cells contain efficient enzyme systems to remove aldehydes in order to avoid such harmful reactions (Kawamura et al., 2002; Svensson et al., 1996). Thus, it would be necessary for such aldehydes to be generated in close proximity to Kv β 2 in order to be effective. However, such a system has not yet been identified. Secondly, there is the issue of competition between aldehydes for Kv β 2 due to its broad specificity. Many aldehydes generated in cells might be expected to compete for the relatively open active site of Kv β 2; this necessitates very tight control of aldehyde access to Kv β 2 for effective, controlled, channel modulation. The requirement for tight control may indicate a high degree of specificity for the true physiological substrate for this reaction. As a result, the true substrate may prove difficult to identify. A final difficulty lies in the requirement that oxidized Kv β 2 bound cofactor must be reduced in order to reset the channel modulation signal following its oxidation by an aldehyde substrate.

It might be argued that the slow rate of aldehyde reduction by Kv β 2 makes it difficult to envisage that such a reaction could modulate channel activity in real time as has been proposed (Tipparaju et al., 2008; Weng et al., 2006). A possible explanation lies in the requirement that the true substrate, as yet unidentified, has a significantly higher turnover than those identified in this and previous studies. Another possibility is that turnover may be upregulated by association of Kv β 2 with the channel subunits or with other proteins or indeed by other signaling events.

Dismutation of aldehydes has proven difficult to monitor since it is a redox silent reaction (Henehan et al., 1995; Oppenheimer and Henehan, 1995). In this study we have devised a sensitive HPLC assay, based on the absorbance of nitrobenzaldehyde and its derivatives, capable of detecting both net aldehyde reduction and aldehyde dismutation. The assay will be generally useful for screening for dismutation, albeit confined to a single substrate. From these studies it is clear that Kv β 2 can dismutate aldehydes but at a rate far slower than HLADH. This is consistent with the slow turnover of aldehyde substrates by aldo-keto reductases from a number of sources when compared to corresponding alcohol dehydrogenases (Barski et al., 2008). Although dismutation was slow it was clear that acid formation was occurring. Control experiments showed no acid formation under the same conditions thereby discounting the possibility that acid formation was due to non-enzymatic aldehyde oxidation. Moreover, acid formation was time dependent and

acid was formed in equimolar concentrations to that of the alcohol product.

If it were postulated that channel activity was controlled by aldehyde dismutation it would obviate the necessity to regenerate reduced Kv β 2-bound cofactor since this reaction alternately oxidizes and reduces NADP(H). Notwithstanding this point, it is difficult to argue for a significant physiological role for the slow dismutation observed here with 4-nitrobenzaldehyde but we cannot discount the possibility that dismutation might be faster for other, as yet untested, substrates. It is of interest for inhibitor design to consider that Kv β 2 is capable of generating a carboxylate, presumably from the hydrated form of the aldehyde, at its active site. A similar dismutation reaction has previously been reported for the carbonyl reductase from pig lung (Hara et al., 1991).

Recent findings have shown that cortisone binds to Kv β 2 and promotes its dissociation from the K⁺ channel (Pan et al., 2008b). Structural studies identified two types of cortisone binding sites on Kv β 2, one close to the bound NADPH and the other at the interface of two neighbouring Kv β subunits (Pan et al., 2008b). Only the interface binding site was reported to be required for channel modulation. These findings indicate that cortisone may act to further regulate aldehyde-mediated channel modulation by promoting Kv β 2 dissociation from α subunits. It is conceivable that fine control of channel activity could be modulated by a specific aldehyde substrate but that cortisone could abolish such control by dissociation of Kv β 2 from the α subunits. The relationship of these two very different modes of K⁺ channel modulation remains to be explored. In particular, data on the influence of low concentrations of cortisone on channel activity would be of great interest since reports to date used concentrations of 500 μ M and above that may be difficult to attain physiologically. Interestingly, cortisone was shown to bind to the active site of Kv β 2 but was not a substrate. Thus, cortisone is expected to act as an inhibitor of aldehyde reduction *in vitro*. Whether aldehyde substrates act in opposition to cortisone or in synergy with cortisone as channel modulators remains to be elucidated.

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References

- Barski OA, Tipparaju SM, Bhatnagar A. The aldo-keto reductase superfamily and its role in drug metabolism and detoxification. *Drug Metab Rev* 2008;40(4):553–624.
- Daussmann T, Aivasidis A, Wandrey C. Kinetic data and new enzymatic activities of *Methanosarcina barkeri* grown on methanol as sole carbon source. *Water Sci Technol* 1997;36:175–82.
- Dolly JO, Rettig J, Scott VE, Parcej DN, Wittkat R, Sewing S, et al. Oligomeric and subunit structures of neuronal voltage-sensitive K⁺ channels. *Biochem Soc Trans* 1994;22:473–8.
- Gulbis JM, Mann S, MacKinnon R. Structure of a voltage-dependent K1 channel β subunit. *Cell* 1999;90:943–52.
- Hara A, Yamamoto H, Deyashiki Y, Nakayama T, Oritani H, Sawada H. Aldehyde dismutation catalyzed by pulmonary carbonyl reductase: kinetic studies of chloral hydrate metabolism to trichloroacetic acid and trichloroethanol. *BBA* 1991;1075(1):61–7.
- Henehan GTM, Chang SH, Oppenheimer NJ. Aldehyde dehydrogenase activity of *Drosophila melanogaster* alcohol dehydrogenase: burst kinetics at high pH and aldehyde dismutase activity at physiological pH. *Biochemistry* 1995;34:12294–301.
- Hille B. Ion channels of excitable membranes. 3rd ed. Sunderland, MA: Sinauer Associates; 1991.
- Kawamura M, Eisenhofer G, Kopin IJ, Kador PF, Lee YS, Fujisawa S, et al. Aldose reductase: an aldehyde scavenging enzyme in the intraneuronal metabolism of norepinephrine in human sympathetic ganglia. *Auton Neurosci* 2002;96:131–9.
- Kolb HA. Potassium channels in excitable and non-excitable cells. *Rev Physiol Biochem Pharmacol* 1990;115:51–91.
- Liu SQ, Jin H, Zacarias A, Srivastava S, Bhatnagar A. Binding of pyridine nucleotide coenzymes to the β -subunit of the voltage-sensitive K⁺ channel. *J Biol Chem* 2001;15:11812–20.
- Long SB, Campbell EB, MacKinnon R. Voltage sensor of Kv1.2: structural basis of electromechanical coupling. *Science* 2005;309:903–8.
- Mee B, Kelleher D, Frias J, Malone R, Tipton KF, Henehan GTM, et al. Characterization of cinnamyl alcohol dehydrogenase of *Helicobacter pylori*, an aldehyde dismutating enzyme. *FEBS J* 2005;272:1255–64.
- Oldendorf WH. Brain uptake of radiolabelled amino acids, amines, and hexoses after arterial injection. *Am J Physiol* 1971a;221:1629–39.
- Oldendorf WH. Uptake of radiolabelled essential amino acids by brain following arterial injection. *Proc Exp Biol Med* 1971b;136:385–6.
- Oppenheimer NJ, Henehan GTM. Horse liver alcohol dehydrogenase-catalyzed aldehyde oxidation. The sequential oxidation of alcohols to carboxylic acids under NADH recycling conditions. *Adv Exp Medical Biol* 1995;372:407–15.
- Orlova EV, Papakosta M, Booy FP, Van Heel M, Dolly JO. Voltage-gated K⁺ channel from mammalian brain: 3D structure at 1.8 Å of the complete (α)₄(β)₄ complex. *J Mol Biol* 2003;326:1005–12.
- Pan Y, Weng J, Cao Y, Bhosle RC, Zhou M. Functional coupling between the Kv1.1 channel and aldo-keto reductase Kv β 1. *J Biol Chem* 2008a;283:8634–42.
- Pan Y, Weng J, Kabaleeswaran V, Li H, Cao Y, Bhosle RC, et al. Cortisone dissociates the Shaker family K⁺ channels from their beta subunits. *Nat Chem Biol* 2008b;4:708–14.
- Parcej DN, Scott VE, Dolly JO. Oligomeric properties of alpha-dendrotoxin-sensitive potassium ion channels purified from bovine brain. *Biochemistry* 1992;31:11084–8.
- Pellerin L. How astrocytes feed hungry neurons. *Mol Neurobiol* 2005;32:59–72.
- Pongs O, Leicher T, Berger M, Roeper J, Bähring R, Wray D, et al. Functional and molecular aspects of voltage-gated K⁺ channel beta subunits. *Ann N Y Acad Sci* 1999;868:344–55.
- Schenkels P, Duine JA, Nicotinoprotein. (NADH-containing) alcohol dehydrogenase from *Rhodococcus erythropolis* DSM 1069 an efficient catalyst for coenzyme-independent oxidation of a broad spectrum of alcohols and the interconversion of alcohols and aldehydes. *Microbiology* 2000;146:775–85.
- Scott VE, Rettig J, Parcej DN, Keen JN, Findlay JB, Pongs O, et al. Primary structure of a beta subunit of alpha-dendrotoxin-sensitive K⁺ channels from bovine brain. *Proc Natl Acad Sci USA* 1994;91:1637–41.
- Shearer GL, Kim K, Lee KM, Wang CK, Plapp BV. Alternative pathways and reactions of benzyl alcohol and benzaldehyde with horse liver alcohol dehydrogenase. *Biochemistry* 1993;32:11186–94.
- Steinbuechel A, Schlegel HG. A multifunctional fermentative alcohol dehydrogenase from the strict aerobic *Alcaligenes eutrophus*: purification and properties. *Eur J Biochem* 1984;141:555–64.
- Svensson S, Lundsjo A, Cronholm T, Hoog JO. Aldehyde dismutase activity of human liver alcohol dehydrogenase. *FEBS Lett* 1996;394:217–20.
- Tipparaju SM, Barski OA, Srivastava S, Bhatnagar A. Catalytic mechanism and substrate specificity of the subunit of the voltage-gated potassium channel. *Biochemistry* 2008;47:8840–54.
- Weng J, Cao Y, Moss N, Zhou M. Modulation of voltage dependant Shaker family potassium channels by an aldo-keto reductase. *J Biol Chem* 2006;281:15194–200.
- Winberg JO, McKinley-McKee JS. *Drosophila melanogaster* alcohol dehydrogenase: mechanism of aldehyde oxidation and dismutation. *Biochem J* 1998;329:561–70.
- Xu J, Li M. Auxiliary subunits of shaker-type potassium channels. *Trends Cardiovasc Med* 1998;8:229–34.
- Yudkoff M, Daikhin Y, Grunstein L, Stern J, Pleasure D, Nissim I. Astrocyte leucine metabolism: significance of branched-chain amino acid transamination. *J Neurochem* 1996;66:378–85.