Amyloid β-Peptide-binding Alcohol Dehydrogenase Is a Component of the Cellular Response to Nutritional Stress*

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Amyloid β-peptide-binding alcohol dehydrogenase (ABAD) is a member of the family of short chain dehydrogenases/reductases whose distinctive properties include the capacity to bind amyloid β-peptide and enzymatic activity toward a broad array of substrates including n-isopropanol and β-estradiol. In view of the wide substrate specificity of ABAD and its high activity on 1,β-hydroxyacyl-CoA derivatives, we asked whether it might also catalyze the oxidation of the ketone body β-hydroxybutyrate. This was indeed the case, and oxidation proceeded with a K_m of 4.5 mM and V_max of 4 nmol/min/mg protein. When placed in medium with β-hydroxybutyrate as the principal energy substrate, COS cells stably transfected to overexpress wild-type ABAD (COS/WTABAD) better maintained 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide reduction, cellular energy charge, and morphologic phenotype compared with COS/vector cells. Using a severe model of metabolic perturbation, transgenic mice with targeted neuronal expression of ABAD subjected to transient middle cerebral artery occlusion showed strokes of smaller volume and lower neurologic deficit scores in parallel with increased brain ATP and decreased lactate, compared with nontransgenic controls. These data suggest that ABAD contributes to the protective response to metabolic stress, especially in the setting of ischemia.

Recent studies of familial Alzheimer’s disease have provided support for a close relationship between accumulation of amyloid β-peptide (Aβ), especially the longer form, Aβ(1–42), and development of cerebral dysfunction leading to dementia (1–4). In sporadic Alzheimer’s disease, there is an emerging view that decreased clearance of Aβ, possibly mediated by a pathway involving low density lipoprotein receptor-related protein, apoE, and/or α_2-macroglobulin, may contribute to the Aβ-rich environment that disturbs cellular properties (5–8). However, much remains to be learned about the pathways through which Aβ actually induces cellular stress. In the presence of high concentrations of Aβ (micromolar range), generation of oxidants, and changes in calcium homeostasis feed into cell death pathways (9–12). To understand mechanisms that might underlie Aβ-induced cell stress rather than rapid induction of cell death, we have sought cell-associated cofactors capable of magnifying the effects of the amyloid peptide on target cells. We reasoned that such cofactors might be relevant to early phases of Alzheimer’s disease when neuronal dysfunction is evolving, but changes are still reversible.

Amyloid β-peptide-binding Alcohol Dehydrogenase (ABAD) is a member of the family of short chain dehydrogenases/reductases (13, 14). It shares features with other members of this family, such as the requirement for a dinucleotide cofactor, nicotinamide adenine dinucleotide (NAD[H]), and a Rossman-fold structural topology with an invariant sequence, Tyr-X-X-Lys, corresponding to residues 168–172 in ABAD, all of which are required for enzymatic activity (15). However, it is distinct from other members of the family in terms of its ability to bind Aβ (13, 14), and its ability to use a broad array of substrates, including linear alcohols, 3-hydroxyacyl-CoA derivatives, and steroids (such as 17β-estradiol) (13, 14, 16–19). In an Aβ-rich environment, ABAD appears to potentiate cell stress induced by the amyloid peptide, as evidenced by increased generation of 4-hydroxynonenal-lysine and malondialdehyde-lysine epitopes and induction of DNA fragmentation (14). Although these observations suggest a “dark side” of ABAD potentially contributing to the pathogenicity of Aβ-induced cellular dysfunction, we reasoned that ABAD is likely to have other properties relevant to normal physiology. Consistent with this concept, inactivation of the Dro sophila counterpart of ABAD, termed scully, resulted in a lethal phenotype with multiple developmental abnormalities (20). These broad enzymatic properties of ABAD suggested that it might facilitate utilization of ketone bodies by promoting the

butyric acid; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide; PDGF, platelet-derived growth factor B-chain; Tg, transgenic; DMEM, Dulbecco’s modified Eagle’s medium; HPLC, high pressure liquid chromatography; PDGF, platelet-derived growth factor.
generation of acetyl-CoA to feed into the tricarboxylic acid cycle. This led us to consider a role for ABAD in the cellular response to nutritional/metabolic stress. For example, ketone bodies can reach appreciable concentrations (3–6 mM) in fasted nonhuman primates, both neonatal and infant animals (21), as well as during starvation in normal humans/adult animals (22, 23). Under these conditions, the oxidation of β-hydroxybutyrate becomes the dominant source for energy production in brain (21–23). In the current study, we demonstrate that ABAD does promote utilization of ketone bodies in a cellular environment, probably at the level of both β-hydroxybutyrate. Furthermore, overexpression of ABAD in COS cells, which have low endogenous levels of this enzyme, maintains cellular functions under conditions where β-hydroxybutyrate is the principal energetic substrate. Using NMR to analyze [13C]β-hydroxybutyrate metabolism, ABAD-transfected COS cells displayed increased flux of acetyl-CoA through the tricarboxylic acid cycle. Because ischemia is a severe metabolic stress, a murine stroke model in transgenic mice was employed to determine consequences of overexpressing ABAD in cortical neurons. ABAD transgenic mice demonstrated a protective phenotype with an ~40% reduction in stroke volume and improvement in neurologic deficit scores. Overexpression of ABAD in Tg mice was associated with increased flux of acetyl-CoA through the tricarboxylic acid cycle and increased ATP in cerebral cortex following infusion of β-hydroxybutyrate. These data indicate that expression of ABAD confers a protective phenotype in response to acute metabolic stress, such as that imposed by ischemia, and provide a starting point for further analysis of the properties of ABAD in complex biologic systems.

MATERIALS AND METHODS

Recombinant ABAD and Metabolism of β-Hydroxybutyrate and β-Hydroxybutyryl-CoA—ABAD was produced recombinantly in Escherichia coli (BL21) and purified to homogeneity as described (14). β- and γ-β-Hydroxybutyrate (sodium salt) and γ-β-hydroxybutyryl-CoA were obtained from Sigma. ABAD oxidation of γ-β-hydroxybutyryl-CoA employed ABAD (330 ng/ml), a range of β-hydroxybutyryl-CoA concentrations (20–1000 μM), and NAD+ (1.2 mM; Sigma) in 75 mM Tris (pH 8.0)/75 mM KCl (17). The reaction was run for a total of 10 min at 30 °C under steady-state conditions (24), and the change in NADH absorbance at 340 nm was determined. ABAD oxidation of either β- or γ-β-hydroxybutyrate employed 150 μg/ml ABAD, a range of β-hydroxybutyrate concentrations (0.4–25 mM), and 5 mM NAD+ in 10 mM Tris (pH 7.4)/0.25 mM NaCl. β-Hydroxybutyrate, NADH, and Tris/NaCl were preincubated for 10 min at 37 °C. Then the enzyme was added, and the reaction was run for a total of 30 min at 30 °C under steady-state conditions as above, except that absorbance at 340 nm was determined (data from the first 10 min were used, when the change in absorbance was linear). Kinetic data were analyzed for Michaelis-Menten using the program. One unit of enzyme activity was defined as that which converts 1 μmol of substrate to product/min.

Generation and Characterization of Stably Transfected COS Cells Expressing ABAD—COS cells (ATCC; 106 cells) were transfected with pcDNA3 (human) wild-type ABAD or mutABAD, or pcDNA3 alone (vector) previously linearized with SmaI, using LipofectAMINE (14). MutABAD, in which residues 168 (Tyr) and 172 (Lys) in the active site have been replaced by glycine, generating an enzymatically crippled mutant (pH 10)/75 mM KCl (17). The reaction was run for a total of 10 min at 30 °C under steady-state conditions where ABAD and Metabolic Stress

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β

C

NMR Spectroscopy—C

NMR spectroscopy is a powerful techni-

cal method for measuring substrate metabolism in situ (30–38). Addition to culture supernatant or perfusing organs with [2,4-13C]β-hydroxybutyrate results in the 13C labeling of tricarboxylic acid cycle intermediates from labeled acetyl-CoA (36, 37). Although tricarboxylic acid cycle intermediates are usually present at concentrations too low to be observed by NMR spectroscopy, glutamate, which is present at millimolar concentrations, is in rapid exchange with α-keto glutarate via aminotransferase reactions. Thus, if 13C-labeled acetyl-CoA enters the tricarboxylic acid cycle, the 13C label will be detectable as [13C]glutamate. For experiments with cultured cells (107 cells/NMR determination), 13C-[2,4-13C]β-hydroxybutyurate (10 mM) was added to DMEM (without glucose or pyruvate) and dialyzed fetal calf serum (10%). For in vitro studies, (15)β-hydroxybutyrate was infused intravenously as follows over 60 min: 0.75 μl [13C]β-hydroxybutyrate administered as a bolus (0.05 ml) followed by a constant infusion with a total volume of 1.15 ml (38). At the end of the infusion, brain samples were freeze-clamped under liquid nitrogen and stored at −80 °C. Frozen tissue (sample sizes were 92 ± 6 and 88 ± 11 mg for Tg and non-Tg mice, respectively) was extracted with perchloric acid and neutralized with sodium hydroxide as described (35–37), and homogenates were lyophilized and resus-

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Water presaturation experiments were ac-

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H NMR Spectroscopy—Water presaturation experiments were acquired on a Bruker 500 MHz spectrometer, using a 10-mm broadband probe tuned to 125.77 MHz. Field homogeneity was optimized by shimming on the D2O lock signal. Spectra were obtained using a 25 kHz sweep width, with 45° pulse and 2.0 ms pulse delay. 1H NMR spectra were acquired using a WALTZ sequence. Each spectrum represents a total of 17,920 scans. The assignment of 13C resonances was based on previously published studies (33, 34, 36–38). Glutamate peak areas were determined using Bruker NMR software and are expressed as ratios with the summed area of the (2,4-13C)β-hydroxybutyrate peaks. In brain extracts, the area measurements for glutamate, glutamine and γ-amino butyric acid (GABA) are compared with spectra obtained from an external standard solution (0.1 mM [13C]acetate) using the same acquisition parameters as above. The 13C NMR spectra of standard solutions of glutamate and GABA were obtained to confirm chemical shifts of these compounds in the brain extracts.

H NMR Spectroscopy—Water presaturation experiments were acquired on the GE500-MHz spectrometer using a 5-mm inverse detection probe (1H observe, with broad band decoupling capabilities). With a sweep width of 5 KHz, a 45° pulse width, and the carrier frequency set on the H2O peak for a 1-s presaturation pulse, 1H spectra were obtained for 256 total scans. Presaturation experiments were performed both with and without heteronuclear 13C decoupling (for assessing the fractional enrichment in glutamate), centered at 40 ppm, with a WALTZ sequence, and ABAD expression was determined.

The region between 2.6–2.0 ppm reveals proton resonances from the C-4 of glutamate. Although the proton resonances corresponding to [13C]-4glutamate are resolvable, the 1H satellites corresponding to [13C]-4glutamate are obscured by other nearby peaks. Accordingly, the fractional enrichment of glutamate cannot be determined by measuring the areas of the proton peaks bound to labeled and nonlabeled carbons, as
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is the case with lactate (32). However, the enrichment of glutamate C-4 may be determined from the increase in intensity of the C-4 glutamate proton resonances following heteronuclear 2D-C decoupling, because these resolvable resonances then correspond to the sum of protons from labeled and unlabeled glutamate (32).

ABAD; Cells and Function: MITT Reduction and Measurement of Cellular Energy Charge—Reduction of MITT was studied, and phase contrast micrographs of COS cells were made as described previously (13, 39). Measurement of cellular energy charge was also performed by previous methods (40). In brief, cultured cells previously incubated in n-β-hydroxybutyrate, DMEM without glucose or sodium pyruvate (Life Technologies, Inc.), and dialyzed fetal calf serum (10%; Life Technologies, Inc.) were washed three times with phosphate-buffered saline. Adenine nucleotides were extracted with perchloric acid (1 M) and subjected to centrifugation through a layer of bromodecane. The supernatant was neutralized with potassium hydroxide and subjected to reversed-phase HPLC (Microsorb C18; Rainin Instruments Co., Woburn, MA). The column eluate was monitored at an absorbance of 254 nm, and nucleotide concentration was calculated from the peak area using Chromatopack CR-4A (Shimadzu Seiki, Kyoto, Japan). At each point the energy charge was calculated as described (41).

Generation and Characterization of ABAD Transgenic Mice—The platelet-derived growth factor (PDGF) B-chain promoter was used to drive overexpression of ABAD in neurons of the central nervous system of Tg mice (42). Transgene constructs were prepared using a previously described method (43, 44). Briefly, the cytomegalovirus immediate/early promoter was excised from the commercial expression vector pCI (Promega, Madison WI), and replaced with an oligonucleotide polylinker. The PDGF B-chain promoter fragment was mobilized as an XhoI fragment (42) and cloned into a unique SpeI site designed within the synthetic linker. The full-length human ABAD cDNA was inserted into the NotI site of the original polylinker. A 3-kilobase fragment containing the promoter, cDNA, and required other sequences was then excised from the plasmid backbone as BamHI fragment and microinjected mouse B6CBAF/J oocytes. The latter were implanted into pseudopregnant females and mated with B6CBAF/J males resulting in the generation of four founders. These were used to produce lines, which were backcrossed eight times into the C57BL6 background. Tg PD-ABAD mice were identified by Southern blotting, and expression of the transgene was monitored by Northern and Western blotting and immunostaining. Southern blotting was performed on DNA extracted from mouse tails, and hybridization was performed with 32P-labeled cDNA probe for ABAD. Northern and immunoblotting utilized the same procedures as above, except that tissue was homogenized in the presence of Trypsin (39) or a leaf buffer (20 mM Tris/HCl pH 7.4, 0.1% Triton X-100, 2 mM phenylmethylsulfonylfluoride, 1 mM EDTA, 10 μg/ml aprotinin, 10 μg/ml leupeptin, and 1 ml of buffer/0.5 gm of tissue). Note that immunoblotting and immunostaining of brain tissue from Tg PD-ABAD mice used anti-human ABAD peptide IgG, which appears to be preferentially immunoreactive with human ABAD, the latter encoded by the transgene (15). Immunostaining was performed on 4% paraformaldehyde-fixed sections (6 μm thick) that were deparaffinized, rehydrated and then stained with rabbit anti-human ABAD peptide IgG (5 μg/ml) followed by goat anti-rabbit biotin-conjugated IgG and ExtrAvidin-conjugated with alkaline phosphatase (Biotin ExtrAvidin kit; Sigma).

Marine Stroke Model—Mice (C57BL6/J, male) were subjected to stroke according to previously published procedures (45) and in accordance with guidelines of the American Academy of Accreditation of Laboratory Animal Care. Following anesthesia, the carotid artery was accessed using the operative approach previously described in detail (46), including division/coagulation of the occipital and pterygopalatine arteries to obtain improved visualization and vascular access. A nylon artery to obtain improved visualization and vascular access. A nylon arterial stump was cauterized to prevent frank hemorrhage. Measurement of relative cerebral blood flow were obtained as previously reported (45–48) using a straight laser doppler flow probe placed 2 mm posterior to the bregma and 6 mm to each side of midline using a stereotactic micromanipulator, keeping the angle of the probe perpendicular to the cortical surface. These cerebral blood flow measurements, expressed as the ratio of ipsilateral to contralateral blood flow, were obtained at base line, immediately prior to middle cerebral artery occlusion, 45 min after middle cerebral artery occlusion, and at several time points after withdrawal of the occluding suture.

Measurement of Cerebral Infarction Volumes—After 24 h, animals were euthanized, and their brains were rapidly harvested. Infarct volumes were determined by determining cerebral blood flow measurements, a score of 2 was given if the animal was noted to be turning toward the ipsilateral side, a score of 3 was given if the animal was observed to spin longitudinally (clockwise when viewed from the tail), and a score of 4 was given if the animal was unresponsive to noxious stimuli. This scoring system has been previously described in mice (45–47) and is based upon similar scoring systems used in rats (49). Immunostaining of cerebral cortex following induction of stroke in wild-type mice was performed as described above using a rabbit polyclonal antibody made using purified recombinant murine ABAD as the immunogen. Quantification of microscopic images was accomplished with the Universal Imaging System.

ATP and lactate/pyruvate ratio were determined in cerebral cortex from control mice and from ischemia versus nonischemic hemispheres of mice subjected to ischemia (measurements were made 24 h after induction of ischemia). Perchloric acid-extracted cerebral cortex was neutralized with sodium hydroxide, and the ATP in the extract was measured using HPLC techniques (50). Lactate, β-hydroxybutyrate, and pyruvate levels in the neutralized extracts were measured using established assays (51).

RESULTS

ABAD Metabolism of β-Hydroxybutyrate—The broad enzymatic properties of ABAD as an oxidoreductase suggested that it might facilitate cellular utilization of ketone bodies, such as β-hydroxybutyrate, a major energetic substrate during nutritional deprivation in vivo. First, we tested whether β-hydroxybutyryl-CoA, a known substrate of bovine liver-derived hydroxycetyl-CoA type II (HADH II/ABAD (17), with our purified E. coli-derived human recombinant ABAD; the reaction fit Michaelis-Menten kinetics with K_m = −134 μM and V_max = −26.3 μmol/min/mg (Fig. 1A). The latter result, obtained with a racemic mixture of β-hydroxybutyryl-CoA, was similar to that observed previously with the bovine liver HADH II (17). Using the same preparation of recombinant ABAD, we then studied the β-hydroxybutyrate; the reaction also fit Michaelis-Menten kinetics with a K_m of −4.5 mM and a V_max of −4 nmol/min/mg (Fig. 1B). With the l-form of β-hydroxybutyrate, the K_m was −1.6 mM and the V_max was −4 nmol/min/mg (Fig. 1C). In a purified system, ABAD is clearly more effective with β-hydroxybutyryl-CoA as a substrate (presumably this is the l-form, which is an intermediate in the fatty acid β-oxidation pathway in mitochondria). However, depending on physiological conditions, certain substrates may turn out to be more abundant, such as β-hydroxybutyrate during periods of starvation when levels of ketone bodies are elevated and, thus, could become relevant. In fact, plasma levels of β-hydroxybutyrate are reported to reach the millimolar range in animals and humans subjected to nutritional deprivation (21–23). Furthermore, β-hydroxybutyryl-CoA is another likely substrate of ABAD in a cellular milieu rich in β-hydroxybutyrate. Thus, ABAD would appear to have the potential to be pivotal for enhancing metabolism of β-hydroxybutyrate.

Characterization of COS Cells Stably Transfected to Overexpress ABAD—COS cells provided a useful model to test our concept that ABAD modulated the cellular response to nutritional stress because of their low endogenous expression of ABAD; low levels of mRNA were present (Fig. 2A, lane 4) and no antigen was detectable (Fig. 2B, lane 7) in lysates of wild-type COS cells. Following stable transfection with pcDNA3
concentration of D- and indicated concentration of DL-
program. Km curve according to the methods are described in the text. The mM).

A droxybutyryl-CoA. is plotted

mRNA (Fig. 2 lane 3). And antigen (Fig. 2 lane b, cos/vector, lane 6) or wild-type COS cells (lane 4), was subjected to Northern analysis (30 μg of total RNA was added to each lane). Membranes were hybridized with 32P-labeled cDNA probe for ABAD, and RNA loading was determined based on the intensity of the 18 S ribosomal RNA band (12%; reduced; 100 μg of total protein was added to each lane) followed by immunoblotting with anti-ABAD IgG (10 μg/ml). In each case (lanes 1–5), protein extracts were obtained from different clones of stable transfectants. The migration of simultaneously run molecular mass standards is shown on the far right side of the gel, C, stably transfected COS cells (COS/ wtABAD, lane a; COS/mutABAD, line b) were subjected to subcellular fractionation by nitrogen bomb cavitation followed by ultracentrifugation through a series of sucrose steps and collection of fractions (1–6). Immunoblotting was performed on fractions using anti-ABAD IgG (lines a and b), anti-GRP78 IgG (line c; as a marker of endoplasmic reticulum), anti-RAGE IgG (line d; as a marker of plasma membrane), and anti-cytochrome c IgG (line e; as a marker of mitochondria).

Stress—In view of ABAD metabolism of D-β-hydroxybutyrate, we tested whether ABAD-transfected COS cells displayed enhanced ability to sustain nutritional stress in an environment where ketone bodies provided the principal energetic source. When COS/vector cells were placed in medium devoid of glucose and supplemented only with dialyzed serum and β-hydroxybutyrate, cellular functions became compromised. In the presence of D-β-hydroxybutyrate (10 mM), reduction of MTT was suppressed by days 4–5 (Fig. 3A), and cellular energy charge decreased in parallel (Fig. 3C). Phase contrast microscopy showed COS/vector cells, initially with a spread morphology on the growth substrate, to become rounded up and toxic in

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FIG. 1. ABAD metabolism of β-hydroxybutyrate and β-hydroxybutyryl-CoA. A, ABAD (330 ng/ml) was incubated with the indicated concentration of 5-β-hydroxybutyryl-CoA and NAD+ (1.2 mM). B and C, ABAD (150 μg/ml) was incubated with the indicated concentration of D-β-hydroxybutyrate (B) or L-β-hydroxybutyrate (C) and NAD+ (5 mM). The velocity (V) of the reaction (units/mg of protein) is plotted versus added substrate concentration. Details of experimental methods are described in the text. The line represents the theoretical curve according to the K_m and V_max values calculated by the computer program.

FIG. 2. Characterization of COS cells stably transfected to overexpress ABAD. A, RNA isolated from stably transfected COS cells, COS/mutABAD (lane 1), COS/wtABAD (lane 2), COS/vector (lane 3), or wild-type COS cells (lane 4), was subjected to Northern analysis (30 μg of total RNA was added to each lane). Membranes were hybridized with 32P-labeled cDNA probe for ABAD, and RNA loading was determined based on the intensity of the 18 S ribosomal RNA band on ethidium bromide-stained gels. B, protein extracts from stably transfected COS cells (COS/mutABAD, lanes 1 and 2; COS/wtABAD, lanes 3–5; and COS/vector, lane 6) or wild-type COS cells (lane 7) were subjected to SDS polyacrylamide gel electrophoresis (12%; reduced; 100 μg of total protein was added to each lane) followed by immunoblotting with anti-ABAD IgG (10 μg/ml). In each case (lanes 1–5), protein extracts were obtained from different clones of stable transfectants. The migration of simultaneously run molecular mass standards is shown on the far right side of the gel. C, stably transfected COS cells (COS/ wtABAD, lane a; COS/mutABAD, line b) were subjected to subcellular fractionation by nitrogen bomb cavitation followed by ultracentrifugation through a series of sucrose steps and collection of fractions (1–6). Immunoblotting was performed on fractions using anti-ABAD IgG (lines a and b), anti-GRP78 IgG (line c; as a marker of endoplasmic reticulum), anti-RAGE IgG (line d; as a marker of plasma membrane), and anti-cytochrome c IgG (line e; as a marker of mitochondria).
appearance after 4 days under these conditions (Fig. 3D, panels I and II). Similar results were obtained when COS/vector cells were replaced with wild-type COS cells, and the same studies described above were performed (not shown). In contrast, COS/wtABAD cells better maintained MTT reduction (Fig. 3A) and cellular energy charge (Fig. 3C) in the presence of β-hydroxybutyrate. These changes in cellular properties were paralleled by maintenance of the morphologic phenotype of COS/wtABAD cells, compared with COS/vector transfectants (Fig. 3D, panels III and IV) in the presence of β-hydroxybutyrate. The effect of β-hydroxybutyrate to maintain cellular functions in COS/wtABAD cells was dose-dependent, as shown using the MTT reduction assay, and reached a plateau by 10 mM (Fig. 3B). Furthermore, experiments with lower concentrations of β-hydroxybutyrate (≤2.5 mM) displayed less effective maintenance of cellular properties with COS/wtABAD cells (not shown). The requirement for enzymatically intact ABAD (wtABAD) for enhanced survival of COS/wtABAD cells in the presence of β-hydroxybutyrate was shown by experiments performed with COS/mutABAD cells. Although the crippled enzyme (mutABAD) was expressed at similar levels and with a similar subcellular distribution as the wild-type enzyme (the latter in COS/wtABAD cells), COS/mutABAD cells responded to glucose replacement with β-hydroxybutyrate as did COS/vector cells;
there was a steady decline in MTT reduction and cellular energy charge (Fig. 3, A and C).

NMR studies were performed on cells incubated with $^{13}$C$^+$-labeled $\beta$-hydroxybutyrate (labeled in the C-2 and C-4 positions) to determine the effect of ABAD on the metabolism of the COS/wtABAD transfectants in medium devoid of glucose. $^{13}$C-Labeled $\beta$-hydroxybutyrate enters the tricarboxylic acid cycle as $^{13}$C-2-labeled acetyl-CoA and is metabolized to $\alpha$-ketoglutarate. Thus, C-4 gets labeled in the first turn of the tricarboxylic acid cycle, and subsequent labeling occurs in the C-3 and C-2 positions. Because $\alpha$-ketoglutarate is in rapid equilibrium with glutamate, the labeling of $^{13}$C-glutamate in the C-4, 3, and 2 positions was observed (Fig. 4A). Because the flux of $^{13}$C-labeled acetyl-CoA via the tricarboxylic acid cycle is orientation conserved, the labeling of $^{13}$C-glutamate is greater in the C-4, compared with the C-3 and C-2, positions. Thus, labeling was evaluated in the C-4 position of glutamate in COS/wtABAD versus COS/vector in cell lysates and supernatants. In culture supernatants, NMR data demonstrated greater labeling of the C-4 resonances in glutamate in COS/wtABAD cells, −2-fold, compared with COS/vector cells (Fig. 4B; $p < 0.03$ at days 4, 6, and 8). Glutamine was not detected in supernatants from COS/wtABAD or COS/vector cells. The $^1$H NMR analysis of these supernatants revealed that the fractional enrichment at glutamate C-4 was $58 \pm 3\%$ in COS/wtABAD transfectants compared with $41 \pm 2\%$ in COS/vector cells. These data are indicative of increased metabolism of exogenous $^{13}$C-labeled $\beta$-hydroxybutyrate in COS cells overexpressing ABAD. In contrast, there were no observed differences between fractional enrichment at glutamate C-4 in cell lysates between COS/wtABAD and COS/vector cells, probably because glutamate is rapidly extruded into the medium (glutamine and glutamate levels in cell lysates were the same, comparing COS/wtABAD and COS/vector cells). The $^{13}$C and $^1$H NMR data demonstrate increased exogenous $\beta$-hydroxybutyrate utilization in the COS cells overexpressing wtABAD.

**Up-regulation of ABAD in Response to Cerebral Ischemia**—A severe form of metabolic stress is imposed by cerebral ischemia. Wild-type C57BL6 mice subjected to transient middle cerebral artery occlusion displayed increased levels of ABAD in neurons near the infarcted area (Fig. 5A), especially those in the penumbra (Fig. 5A, inset), compared with the nonischemic hemisphere (Fig. 5B), using polyclonal antibody to recombinant mouse ABAD. Image analysis of sections similar to those shown in Fig. 5 (A and B) demonstrated an ~5-fold increase of ABAD antigen in cortical neurons consequent to stroke (Fig. 5C).

**Characterization of Tg PD-ABAD Mice**—These data with wild-type mice subjected to cerebral ischemia suggested that up-regulation of ABAD might be a component of the response to ischemic stress and led us to make transgenic mice in which ABAD was overexpressed in cortical neurons. Three independent founders of Tg mice in which human ABAD is expressed under control of the human PDGF B-chain promoter have been identified and used to establish transgenic lines (at present backcrossed eight times into the C57BL6 background). Representative mice from each of these transgenic lines showed high levels of transgene activity at both the mRNA (Fig. 6A) and protein levels (Fig. 6B) in cerebral cortex. Immunoblotting performed on brain subregions from one line of Tg PD-ABAD mice, using an anti-human ABAD peptide antibody that selectively recognizes the human form of the protein, showed increased antigen especially in cerebral cortex and hippocampus, with a smaller increase in cerebellum (Fig. 6C). Immunohistochemical staining of ABAD in cerebral cortex confirmed high levels of antigen expression in cortical neurons (Fig. 6D) compared with nontransgenic littermates (Fig. 6D). Semiquantitative analysis of immunohistochemical results using antibody reactive with murine and human ABAD antigen (i.e. total ABAD antigen) indicated that there was an ~3.5−4-fold increase in total ABAD antigen in cerebral cortex comparing Tg mice with non-Tg littermate control mice (Fig. 6D). Induction of stroke in transgenic mice further elevated ABAD antigen another 2-fold compared with non-Tg controls (24 h after the ischemic episode; not shown). Growth (height/weight) and reproductive fitness (number and size of litters) was similar between Tg PD-ABAD mice and nontransgenic (non-Tg) controls, and there were no overt neurologic symptoms or other phenotype evident in these mice noted to date.

**NMR Analysis of $^{13}$C $\beta$-Hydroxybutyrate Metabolism in Tg PD-ABAD Mice**—Tg PD-ABAD and control mice were infused with $[\text{2,4}, \text{13}$C$]3\text{-hydroxybutyrate}$. $^{13}$C NMR spectra of cerebral cortical extracts from Tg PD-ABAD and non-Tg littermate control (the latter spectra are not shown) mice illustrate labeling of glutamate and glutamine in the C-4, C-3, and C-2 positions, as well as GABA in the C-2 position (Fig. 7A), consistent with entry of $^{13}$C$\beta$-hydroxybutyrate via 2-[13C]acetyl-CoA into the tricarboxylic acid cycle. The intensity of glutamate and glutamine C-4 resonance was 50 and 20% greater, respectively, in Tg PD-ABAD mouse brain compared with non-Tg littermates (Fig. 7B). The glutamate to glutamine ratio, based on C-4 resonance area, was $3.6 \pm 0.3$ in non-Tg versus $2.1 \pm 0.4$ in Tg PD-ABAD mouse brains ($p < 0.03$). These data suggest that glutamine synthesis is more efficient in Tg PD-ABAD mouse brain compared with controls. The area of the $^{13}$C-labeled C-2 resonance of GABA was also greater in Tg PD-ABAD mice ($4.8 \pm 0.3$) than in non-Tg control $(2.2 \pm 0.5$, $p < 0.04$). Such increased labeling of GABA is consistent with enhanced conversion of labeled glutamate to GABA in brains of Tg mice. $^1$H NMR analysis of these extracts revealed that the fractional enrichment in glutamate C-4 was significantly greater in Tg PD-ABAD ($58 \pm 5\%$) than in non-Tg littermates ($38 \pm 7\%$, $p < 0.03$). As might be expected from the increased utilization of exogenous $\beta$-hydroxybutyrate, measurement of basal ATP levels in cerebral
Cortex of Tg PD-ABAD mice fasted overnight showed a statistically significant increase compared with non-Tg littermates (Fig. 7C). Similarly, levels of β-hydroxybutyrate in the brains of Tg PD-ABAD mice were lower, compared with non-Tg controls (Fig. 8D). This is consistent with increased utilization of β-hydroxybutyrate in the presence of higher levels of neuronal ABAD.

**Induction of Stroke in Tg PD-ABAD Mice**—To assess the possible contribution of ABAD to ischemic stress, Tg PD-ABAD and age-matched non-Tg littermate control mice were subjected to a 45-min period of transient middle cerebral artery occlusion followed by a 24-h period for evolution of the cerebral infarct. These studies utilized a protocol that we have found to provide reproducible stroke volumes and functional data (neurologic deficit scores, cerebral blood flow) (45–48). Levels of ABAD increased an additional ~2-fold in Tg PD-ABAD mice after stroke, versus with untreated/control Tg PD-ABAD mice. Compared with non-Tg littermate controls, Tg PD-ABAD mice displayed strokes of smaller volume and lower neurologic deficit scores (consistent with better maintenance of neurologic function) (Fig. 8, A and B). In contrast, there was no change in cerebral blood flow comparing the Tg and non-Tg animals (not shown), consistent with a direct effect of ABAD on neurons, as ABAD was overexpressed in neurons by the PDGF B-chain promoter. Analysis of cerebral cortex from Tg animals showed increased ATP and decreased lactate levels compared with non-Tg controls (Fig. 8C). In addition, β-hydroxybutyrate levels were lower in animals subjected to cerebral ischemia, and this finding was much more pronounced in Tg PD-ABAD mice compared with non-Tg littermate controls (Fig. 8D). These data
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ABAD is a member of the short chain dehydrogenase/reductase family with remarkably broad substrate specificity, now extended to include the ketone body D-β-hydroxybutyrate. In comparison with mitochondrial D-β-hydroxybutyrate dehydrogenase (52–55), which displays a $K_m \sim 1 \text{ mM}$, ABAD displays a $K_m$ of $\sim 4.5 \text{ mM}$. At β-hydroxybutyrate concentrations in the plasma of normal individuals ($<1 \text{ mM}$), both enzymes would be working considerably below their respective $K_m$ values. Under pathologic conditions, when β-hydroxybutyrate concentrations can reach the millimolar range (21–23), both enzymes would be expected to metabolize β-hydroxybutyrate. However, the maximal activity of ABAD with D-β-hydroxybutyrate (0.0039 μmol/min/mg) is much lower than that for the mitochondrial enzyme ($V_{\text{max}} = \sim 100–175 \mu\text{mol/min/mg}$ protein with β-hydroxybutyrate) (54, 55). D-β-Hydroxybutyrate dehydrogenase is a housekeeping metabolic enzyme present in mitochondria whose expression has not been reported to vary in pathologic states, beyond its loss from severely ischemic cardiac tissue (56, 57). ABAD, present in both endoplasmic reticulum and mitochondria, displays a pattern of expression sensitive to environmental perturbations, including increased expression in brains of patients with Alzheimer’s disease (13) and at sites of ischemic brain injury (Fig. 5). Thus, in settings where ABAD expression is enhanced, the enzyme could, potentially, contribute to the metabolism of β-hydroxybutyrate. However, the situation is likely to be more complex in vivo, because Tg PD-ABAD mice display increased flux of acetyl-CoA through the tricarboxylic acid cycle and higher ATP levels in the cerebral cortex, even though the level of ABAD expression is only increased by about 3.5–4-fold, compared with nontransgenic controls. These data indicate that ABAD clearly has the potential to contribute to β-hydroxybutyrate metabolism, although the extent of its contribution is likely to depend on the particular situation.

Increased expression of ABAD in human brain following cerebral infarction² and in response to experimentally induced cerebral ischemia (Fig. 5) suggests that induction of ABAD might subserve normal protective mechanisms. In view of the complexities of cellular metabolic pathways, it was necessary to prove that ABAD could promote metabolic homeostasis in response to nutritional deprivation. ABAD-transfected COS cells displayed increased energy charge and flux of acetyl-CoA through the tricarboxylic acid cycle in medium containing β-hydroxybutyrate compared with controls in which the active site of ABAD was mutationally inactivated. Enhanced metabolic homeostasis was reflected by maintenance of MTT reduction and morphologic phenotype in ABAD-transfected COS cells. Similarly, transgenic mice overexpressing ABAD in cortical neurons demonstrated increased flux of acetyl-CoA through the tricarboxylic acid cycle following β-hydroxybutyrate infusion compared with nontransgenic littermates. However, increased basal levels of ATP (and energy charge; data not shown) in brains of Tg PD-ABAD mice, even before nutritional stress, suggested better maintenance of energy reserve and substrate metabolism in Tg PD-ABAD mice subjected to ischemia.

**DISCUSSION**

The effect of ABAD overexpression on the proton-decoupled $^{13}$C NMR spectra of freeze-clamped brain after perfusion with [2,4-$^{13}$C]$^2$D-β-hydroxybutyrate. A, the spectrum from a representative Tg PD-ABAD mouse displays prominent glutamate and glutamine peaks. The inset shows expanded regions of resonances of glutamate (G-4), glutamine (GL-4), and GABA (GA-2) from Tg (PD-ABAD) mice. G-2, G-3, and G-4 denote the position 2, 3, and 4 carbons of glutamate, respectively; GL-2, GL-3, and GL-4 denote the position 2, 3, and 4 carbons of glutamine, respectively; and GA-2 corresponds to C-2 of GABA. B, the effect of ABAD overexpression on areas of glutamate C-4 resonance in brain extracts of Tg PD-ABAD and non-Tg littermate control mice as obtained from $^{13}$C NMR analysis. Values are expressed as the ratio of the area of the glutamate C-4 peak over the area of an added standard acetate (see "Materials and Methods"). The asterisk indicates glutamate and glutamine levels significantly higher in Tg PD-ABAD mice than in non-Tg controls ($p < 0.03; n = 4$, in each case). Total areas of $[^{13}$C$]$glutamate (G-2 + G-3 + G-4) were significantly higher in the Tg PD-ABAD compared with nonTg littermate mice.

C, basal ATP levels in whole brain extracts from Tg PD-ABAD ($n = 5$) or non-Tg littermate controls ($n = 5$) were measured as described in the text. Animals were fasted overnight, and the brain was removed and freeze-clamped for ATP and β-hydroxybutyrate analysis. The asterisk indicates $p < 0.03$. In each case, the data are reported as the means ± S.D.
were unexpected and suggest a more general protective potential of ABAD in response to a range of environmental challenges. This apparent increase in the overall energy charge in the presence of ABAD implies that the enzyme may render neurons metabolically more stable and, thus, less susceptible to fluctuations in substrate availability.

A decreased lactate content in the cerebral cortex of Tg PD-ABAD mice subjected to stroke suggests two important events associated with neuroprotection. First, decreased tissue lactate and lower lactate/pyruvate ratio in the Tg PD-ABAD mice are indicative of diminished cytosolic NADH/NAD⁺ ratio and consistent with decreased reductive stress. In this context, studies have suggested that diminished in reductive stress may translate into lower reactive oxygen species generation upon reperfusion (58). Second, decreased tissue lactate is also indicative of efficient lactate efflux in stroke-prone tissue, thereby alleviating feedback inhibition brought about by metabolic intermediates of glycolysis (59–61).

Our NMR measurements were based on conversion of α-keto glutarate, an intermediate in the tricarboxylic acid cycle, to glutamate. However, we also observed conversion of glutamate, thus formed, to glutamine and GABA. These data indicate that ketone bodies, such as β-hydroxybutyrate, can provide both a substrate for maintenance of cellular energy charge, as well as a source for increased production of neurotransmitters. To our knowledge, this is the first time that the conversion of labeled β-hydroxybutyrate to GABA and glutamate has been demonstrated in vivo. Furthermore, the increased production of 13C-labeled GABA and glutamate from [13C]β-hydroxybutyrate in Tg PD-ABAD mice, compared with controls, indicates that ABAD provides a novel means for sustaining energy production and replenishing neurotransmitters in the brain using ketone bodies as the substrate. At this point, it is unclear whether neuroprotection afforded by overexpression of ABAD is due solely to its effect on ATP levels and/or changes in neurotransmitter metabolism.

In contrast to this cytoprotective facet of ABAD biology, we have proposed that in the presence of Aβ, another, quite different, aspect of the properties of ABAD becomes manifest (14). In an Aβ-rich environment, ABAD generates reactive oxygen intermediates and toxic reactive aldehydes based on cotransfection experiments using cultured COS and neuroblastoma cells (14). Furthermore, pilot studies with double transgenic mice, resulting from a cross of Tg PD-ABAD mice with transgenic mice overexpressing mutant βAPP, have shown accelerated expression of cell stress markers (4-hydroxynonenal and heme oxygenase type 1), compared with single transgenic mice, and nontransgenic controls. Based on these data, ABAD appears to have chameleon-like properties depending on the local environment, in particular related to the presence of Aβ. Our future studies have the goal of determining how the properties of ABAD become modulated in an Aβ-rich environment and whether this translates into accelerated and more severe neuronal dysfunction/toxicity. The current studies provide a foundation for evaluating metabolic properties of ABAD in response to cellular stress in vitro and in vivo.