



ELSEVIER

Contents lists available at ScienceDirect

Redox Biology

journal homepage: www.elsevier.com/locate/redox

Research Paper

Low sulfide levels and a high degree of cystathionine β -synthase (CBS) activation by S-adenosylmethionine (SAM) in the long-lived naked mole-ratMaja Dziegielewska^{a,*}, Susanne Holtze^b, Christiane Vole^c, Ulrich Wachter^d, Uwe Menzel^e, Michaela Morhart^b, Marco Groth^a, Karol Szafranski^a, Arne Sahn^a, Christoph Sponholz^{a,f}, Philip Dammann^{c,g}, Klaus Huse^a, Thomas Hildebrandt^{b,1}, Matthias Platzer^{a,1}^a Genome Analysis, Leibniz Institute on Aging – Fritz Lipmann Institute (FLI), Beutenbergstraße 11, 07745 Jena, Germany^b Reproduction Management, Leibniz Institute for Zoo & Wildlife Research, Alfred-Kowalke-Straße 17, 10315 Berlin, Germany^c Department of General Zoology, University of Duisburg-Essen, Universitätsstraße 2, 45141 Essen, Germany^d Klinik für Anästhesiologie, Universitätsklinikum, Albert-Einstein-Allee 23, 89081 Ulm, Germany^e Leibniz Institute for Natural Product Research and Infection Biology – Hans-Knöll-Institute (HKI), Beutenbergstraße 11a, 07745 Jena, Germany^f Department of Anaesthesiology and Intensive Care Therapy, Jena University Hospital, Erlanger Allee 101, 07747 Jena, Germany^g Central Animal Laboratory, University Hospital, University of Duisburg-Essen, Hufelandstraße 55, 45122 Essen, Germany

ARTICLE INFO

Article history:

Received 16 December 2015

Received in revised form

12 January 2016

Accepted 12 January 2016

Available online 14 January 2016

Keywords:

Transsulfuration

Hydrogen sulfide

Methionine

Longevity

Mole-rats

Low methionine diet

ABSTRACT

Hydrogen sulfide (H₂S) is a gaseous signalling molecule involved in many physiological and pathological processes. There is increasing evidence that H₂S is implicated in aging and lifespan control in the diet-induced longevity models. However, blood sulfide concentration of naturally long-lived species is not known. Here we measured blood sulfide in the long-lived naked mole-rat and five other mammalian species considerably differing in lifespan and found a negative correlation between blood sulfide and maximum longevity residual. In addition, we show that the naked mole-rat cystathionine β -synthase (CBS), an enzyme whose activity in the liver significantly contributes to systemic sulfide levels, has lower activity in the liver and is activated to a higher degree by S-adenosylmethionine compared to other species. These results add complexity to the understanding of the role of H₂S in aging and call for detailed research on naked mole-rat transsulfuration.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Hydrogen sulfide (H₂S) is a gasotransmitter playing a role in many physiological and pathological processes e.g. inflammation, apoptosis, cellular energetics, vascular contractility. Known molecular mechanisms underlying H₂S effects include activation of ion channels, regulation of second messengers

* Corresponding author.

E-mail addresses: maja.dziegielewska@leibniz-flj.de (M. Dziegielewska), holtze@izw-berlin.de (S. Holtze), christiane.vole@uni-due.de (C. Vole), ulrich.wachter@uni-ulm.de (U. Wachter), Uwe.Menzel@hki-jena.de (U. Menzel), morhart@izw-berlin.de (M. Morhart), marco.groth@leibniz-flj.de (M. Groth), karol.szafranski@leibniz-flj.de (K. Szafranski), arne.sahn@leibniz-flj.de (A. Sahn), Christoph.Sponholz@med.uni-jena.de (C. Sponholz), Philip.Dammann@uk-essen.de (P. Dammann), klaus.huse@leibniz-flj.de (K. Huse), HILDEBRANDT@izw-berlin.de (T. Hildebrandt), matthias.platzer@leibniz-flj.de (M. Platzer).

¹ These authors contributed equally to this work.

<http://dx.doi.org/10.1016/j.redox.2016.01.008>

2213-2317/© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

(cAMP, cGMP, free calcium) levels, and protein sulphydration [1]. In mammals, H₂S is produced mainly by two enzymes of the evolutionarily conserved transsulfuration pathway, cystathionine β -synthase (CBS, EC 4.2.1.22) and cystathionine γ -lyase (CSE, EC 4.4.1.1), as well as 3-mercaptopyruvate sulfurtransferase (MST, EC 2.8.1.2).

CBS is a key regulatory enzyme at the intersection of the transsulfuration pathway and methionine cycle, controlling the flux of methionine into transsulfuration (Fig. 1B). In the canonical reaction CBS catalyses condensation of homocysteine and serine to form cystathionine and water. However, when cysteine is used instead of serine, cystathionine and H₂S are produced. CBS is a pyridoxal 5'-phosphate and heme dependent enzyme consisting of three structural domains: (i) N-terminal heme binding domain, (ii) catalytic core, and (iii) C-terminal regulatory domain with an autoinhibitory function (Fig. 1A). Binding of a universal methyl group donor S-adenosylmethionine (SAM) to the regulatory domain activates and stabilizes the enzyme [2,3].

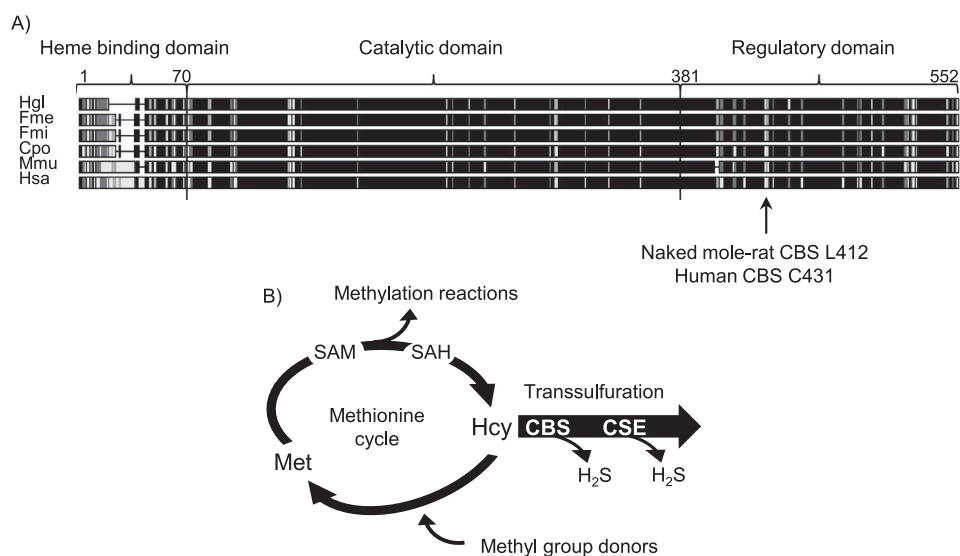


Fig. 1. CBS – an H₂S producing enzyme. (A) Six-species CBS sequence alignment. CBS consists of three domains. The mole-rat C412L substitution is located in the regulatory domain. Hgl – *H. glaber*, Fme – *F. mechowii*, Fmi – *F. micklemi*, Cpo – *C. porcellus*, Mmu – *M. musculus*, Hsa – *H. sapiens* (B) A simplified scheme showing the role of CBS in sulfur metabolism. Met – methionine, hcy – homocysteine.

Although there is increasing evidence that H₂S is implicated in aging and lifespan control, its exact role in these processes is still not clear. Exogenous H₂S increases lifespan in *Caenorhabditis elegans* [4]. Moreover, CBS is required for the life-prolonging effect of caloric restriction in *Drosophila* [5], and increased H₂S production in models for diet-induced longevity was observed [6]. In contrast, a decrease in CBS protein levels and activity in response to methionine and isocaloric protein restriction, respectively, was shown [2,7].

Importantly, sulfide concentration in naturally long-lived species remains unknown. A measure of longevity employed in this study is maximum longevity residual, which represents the relationship of the observed maximum lifespan of the species to its expected, body size-based lifespan calculated with the mammalian allometric equation [8]. Human and naked mole-rat belong to species with the highest maximum longevity residual. The naked mole-rat (*Heterocephalus glaber*) is a eusocial subterranean rodent native to East Africa. It has become the focus of increased attention in the field of aging and cancer research due to its extremely long life- and healthspan [9] as well as its resistance to cancer [10]. Here, we determine blood sulfide concentrations in six mammals (naked mole-rat, human, mouse, guinea pig, *Fukomys mechowii*, *Fukomys micklemi*) differing in their maximum longevity residual. In addition, since CBS activity in the liver significantly contributes to the circulating H₂S levels [11], we comparatively analyse the naked mole-rat CBS gene.

2. Material and methods

2.1. Animals

Naked mole-rat colonies are maintained at Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany in an artificial burrow system with tunnels and plexiglass boxes. The system is heated to 26–29 °C with a constant high relative humidity of 60%–80%. The chambers contain wood bedding, twigs and unbleached paper tissue. Fresh food is given daily *ad libitum* and includes sweet potatoes, carrots, fennel, apples, a cereal supplement containing vitamins and minerals, and oat flakes. Sampling was approved by the local ethics committee of the “Landesamt für Gesundheit und Soziales”, Berlin, Germany (#ZH 156).

F. micklemi and *F. mechowii* are maintained at the animal facilities of the Department of General Zoology, University of Duisburg-Essen, Germany. They are housed as family groups in glass terraria on horticultural peat and fed *ad libitum* with carrots and potatoes every day, apples every second day, and grain and lettuce once a week. Room temperature and humidity is kept constant at 24 ± 1 °C and 40 ± 3%, respectively. Sampling was approved by Landesamt für Natur-, Umwelt- und Verbraucherschutz Nordrhein-Westfalen (Az. 84-02.04.2013.A164).

Guinea pigs (*Cavia porcellus*, Dunkin Hartley HsdDhl:DH) were purchased from Harlan Laboratories, AN Venray, Netherlands. Animals are maintained at Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany under room conditions in plastic cages with litter and hay as bedding. The range of the room temperature is 18–20 °C and of the humidity 40–50%. Fresh food is given daily and includes carrot, cucumber, salad, apples, and dry feed. Sampling was approved by the local ethics committee of the “Landesamt für Gesundheit und Soziales”, Berlin, Germany (G02217/12).

Mice (*Mus musculus*, C57BL/6) were maintained at the Center of Sepsis Control and Care (Jena University Hospital, Jena, Germany). They were maintained under artificial day-night conditions at room temperature, and received a standard diet and water *ad libitum*. Animals were randomly selected for each experiment. Sampling was approved by Thüringer Landesamt für Verbraucherschutz (02-035/12).

2.2. Human samples

Blood samples were obtained from healthy volunteers of European origin after written informed consent and approval by the Jena University Ethics Committee (3624-11/12).

2.3. Quantification of sulfide in whole blood

Sulfide was measured by GC/MS after extractive alkylation using a bis-pentafluorobenzyl derivative. The method and its calibration were described in detail in [12]. 25 µl blood was used and the volume of the reaction mixture was adjusted accordingly. Species and sampling information is listed in Table 1.

Blood sulfide level was correlated with maximum longevity residual obtained from the AnAge database (<http://genomics.senescence.info/species> accessed on 14.09.2015). Of note, there are

Table 1
Species and sampling information for sulfide measurement in blood.

Species	Mean age ± SD	Number of females		Number of males		Source of blood	Anesthesia
		Breeder	Non-breeder	Breeder	Non-breeder		
Hgl	44 months ± 5	3	2	2	3	Heart puncture/vein	Isoflurane
Fme	56 months ± 15		9		7	Vein	Ketamine and xylazine
Fmi	31 months ± 15	2	6	2	9	Vein	Ketamine and xylazine
Mmu	9 months ± 5		4		17	Retro-orbital puncture	Isoflurane
Cpo	12 months		1		3	Heart puncture	Medetomidine, midazolam, and fentanyl
Hsa	45 years ± 11		5		9	Vein	–

Hgl – *H. glaber*, Fme – *F. mechowii*, Fmi – *F. micklei*, Cpo – *C. porcellus*, Mmu – *M. musculus*, Hsa – *H. sapiens*.

no entries for *F. mechowii* and *F. micklei* in the AnAge database. Therefore, maximum longevity residual for *F. mechowii* was calculated with the allometric equation provided by the database: $t_{max} = 4.88M^{0.153}$, t_{max} – maximum longevity, M – body weight. According to our records, the longest living individual of *F. mechowii* is 21yo breeding female, and the mean body weight of *F. mechowii* females is 250 g (unpublished data).

F. micklei is a small bathyergid occurring in Western and Southern Zambia. The maximum lifespan of this species is not yet established because it has been assigned species status only relatively recently [13] and has been bred in laboratories only since 2008. However, *F. micklei* is very closely related to the better studied *F. anelli* and *F. kafuensis*, with all three species belonging to the same “*Fukomys micklei*” clade according to [14]. *F. micklei* interbreeds with *F. anelli* in the lab (own unpublished data), and both species are nearly undistinguishable regarding their body measures and biology including mating and social system. We therefore used the maximum longevity residuals of *F. anelli* as the currently best available approximation for *F. micklei*.

2.4. Cell culture

HCT116 cells were purchased from ECACC through Sigma (Sigma-Aldrich, St. Louis, MO, USA). Cells were grown at 37 °C in the presence of 5% CO₂ in McCoy's Medium (Gibco, Invitrogen GmbH, Karlsruhe, Germany) supplemented with 10% FBS.

HEK293-EBNA cells were a kind gift from Dr. Christoph Kaether (Leibniz Institute for Age Research-Fritz Lipmann Institute, Jena, Germany). Cells were grown at 37 °C in the presence of 5% CO₂ in DMEM Medium (Gibco, Invitrogen GmbH, Karlsruhe, Germany) supplemented with 10% FBS.

2.5. RT-PCR

RNA was isolated using RNeasy Mini Kit (Qiagen, Valencia, CA, USA) according to manufacturer's instructions. 900 ng total RNA was used for reverse transcription with QuantiTect Reverse Transcription Kit (Qiagen, Valencia, CA, USA). *CBS* and *GAPDH* were amplified with the use of primers listed in Table 2 and following PCR conditions: 95 °C 1 min, followed by 29 cycles with 95 °C 30 s,

59 °C 30 s, 72 °C 1 min, and final extension at 72 °C for 10 min. PCR products were analyzed by agarose (1% w/v) gel electrophoresis.

2.6. RNA-seq

For library preparation 1 µg of total RNA was introduced into Illumina's (Illumina, San Diego, CA, USA) TruSeq RNA sample prep kit v2 following the manufacturer's instruction. Quality checking and quantification of the library was done using an Agilent Bioanalyzer 2100 in combination with an Agilent DNA 7400 kit (Agilent Technologies, Inc., CA, USA). The library was sequenced on a Hi-Seq2500 in high-output, 50 bp single-read mode. SBS sequencing chemistry v3 was used (Illumina, San Diego, CA, USA). Read information were extracted in FastQ format using bcl2fastq v1.8.4 (supported by Illumina). The sequencing approach resulted in 57,815,446 single-end reads. The reads were mapped to the human genome (hg19) taken the RefSeq [15] annotation (release 64) into account using tophat v1.4.1 [16]. The mapping result was introduced into htseq-count [17] using the annotation as mentioned above to count reads per gene.

2.7. Test for positive selection

Orthologous genes were determined by best-bidirectional-blast-hits. Per species (*Mus musculus*, *Rattus norvegicus*, *Mesocricetus auratus*, *Cricetulus griseus*, *Nannospalax galili*, *Chinchilla lanigera*, *Cavia porcellus*, *F. mechowii*, *F. micklei*, *Canis lupus*, *Bos taurus*, *Pan troglodytes*, *Homo sapiens*, *Oryctolagus cuniculus*) that splice variant was chosen that showed highest similarity to naked mole-rat transcript (XM_004885703). Codon alignments were conducted using prank [18]. The alignments were filtered by gBlocks [19]. Next, PAML's [20] branch-site test of positive selection was applied using naked mole-rat as foreground branch.

2.8. Plasmids and site-directed mutagenesis

The CBS CDS of naked mole-rat (XM_004885703), *F. mechowii* (KR028540), human (NM_000071), C431L and C431S variants, and human core with naked mole-rat regulatory domain were synthesized and cloned into pCMV6-AC plasmid by Blue Heron

Table 2
Primer sequences used for RT-PCR analysis, site-directed mutagenesis, and cloning.

Gene	Primer names and sequences (5'-3')
<i>CBS</i>	cbs_qPCRhum_1F: ATGCTGATCGCGCAAGAG; cbs_qPCRhum_1R: TCGCTCAGGAACCTGGTCAT
<i>GAPDH</i>	hs_GAPDH_1F: AACGGGAAGCTTGTCATCAATGGA; hs_GAPDH_1R: GCATCAGCAGAGGGGGCAGAG
<i>Mmu CBS</i>	mcbScDNA_EcoRI_1F: TCTAGGAATTCGACCCATCCTTGCTGAGTTTGT; mcbScDNA_PmeI_1R: CTAATGTTTAAACTCGATTGGGTGAGGAAGCTGCTAG
Hgl CBS CT1234TG	nmrCBSMut_1F: CCCACCGTCACCTGCGAGCACACCATC; nmrCBSMut_1R: GATGGTGTGCTCGCAGGTGACGGTGGG
Hgl CBS CT1234TC	nmrCBS_L412S_f: TGCTGCCACCGTCACCTCCGAGCACACCATCGCCAT; nmrCBS_L412S_r: ATGGCGATGGTGTGCTCGGAGGTGACGGTGGGCGAGCA
Fme CBS T355C T358G	CBSmechToAnsel_2F: GAGGACGCAGAGCGCGCCGGATCCT; CBSmechToAnsel_2R: AGGATCCCGCGCGCTCTCGCTCTCTC

Hgl – *H. glaber*, Fme – *F. mechowii*, Mmu – *M. musculus*.

Biotechnology, Inc. (Bothell, WA, USA). The naked mole-rat L412C and L412S variants, and the *F. micklemi* CDS (KR028541) were generated by site-directed mutagenesis using the naked mole-rat or *F. mechowii* pCMV6-AC constructs as a template. Primers containing desired mutations were designed with the primer-design program PrimerX (<http://www.bioinformatics.org/primerx>. Accessed 3 September 2014). The template replicated with Pfu/Psp DNA polymerase (GeneON, Ludwigshafen am Rhein, Germany) was digested with DpnI (NEB, Ipswich, MA, USA).

CDS with naked mole-rat core and human regulatory domain was created by exchanging regulatory domains between human and naked mole-rat pCMV6-AC constructs. Eco47III (Thermo Scientific, Waltham, MA, USA) (restriction site spanning nucleotides 1103 to 1108 of human CBS coding sequence) and PmeI (Thermo Scientific, Waltham, MA, USA) (restriction site in the multiple cloning site) were used to cut plasmids. The fragments were separated on a 1% agarose gel, purified with GeneJET Gel Extraction Kit (Thermo Scientific, Waltham, MA, USA), and ligated with the Quick Ligation Kit (NEB, Ipswich, MA, USA).

Mouse CDS (NM_178224) was amplified using mouse liver cDNA from MTC Multiple Tissue cDNA Panels (Clontech, Mountain View, CA, USA) as a template. Primers contained EcoRI and PmeI restriction sites. PCR product and pCMV6-AC plasmid were digested with EcoRI (NEB, Ipswich, MA, USA) and PmeI (Thermo Scientific, Waltham, MA, USA) and purified from 1% agarose gel with GeneJET Gel Extraction Kit (Thermo Scientific, Waltham, MA, USA). PCR product was ligated into the plasmid with the Quick Ligation Kit (NEB, Ipswich, MA, USA).

All plasmids were amplified in *E. coli* TOP10 cells (Life technologies, Carlsbad, CA, USA) and purified with a Plasmid Maxi Prep kit (Qiagen, Valencia, CA, USA). Plasmid sequences were confirmed by Sanger sequencing using BigDye Terminator v3.1 Sequencing Standard Kit (Applied Biosystems, Foster City, USA) and ABI3730xl DNA Analyzer. All primer sequences are listed in Table 2.

2.9. CBS activity assay

HCT116 cells were transiently transfected with FugeneHD (Promega, Madison, WI, USA) according to manufacturer's protocol using 4:1 reagent:DNA ratio. Cells were harvested 24 or 48 h after transfection and cell pellets were lysed in STEN buffer (50 mM Tris HCl, 150 mM NaCl, 2 mM EDTA, 0.2% NP40, pH 8) supplemented with Halt Protease Inhibitor Cocktail (Thermo Scientific, Waltham, MA, USA). Protein concentration was measured with Pierce BCA Protein Assay Kit (Thermo Scientific, Waltham, MA, USA).

CBS activity was assayed by measurement of H₂S production with an H₂S specific probe 7-azido-4-methylcoumarin (AzMC) (Sigma-Aldrich, St. Louis, MO, USA). The assay was designed after [21]. The reaction mixture contained: 200 mM Tris HCl pH 8.0, 5 μM pyridoxal 5'-phosphate, 10 mM glutathione, 0.5 mg/mL BSA, 50 μM AzMC and cell lysate. Always the same amount of protein was used within one assay. The reaction mixture was incubated with or without SAM (0.5 mM) for 60 min at 37 °C. Always cell lysate from one transfection was divided and used for the measurement in the absence and the presence of SAM. The fluorescence at 450 nm (exc. 365 nm) was read with Infinite M1000 microplate reader (Tecan, Männedorf, Switzerland). Data were normalized to mock transfected cells. Fold activation was calculated by dividing CBS activity with SAM by CBS activity without SAM.

2.10. H₂S producing CBS activity in the liver

Liver tissue from 8 non-breeding naked mole-rats and 8 mice (equal number of both sexes, mean age was 40 months ± 6 and 8 months ± 0.5, respectively) was cut into pieces and frozen

immediately after collection and kept at –20 °C until usage. Liver pieces were disrupted in Tissue Lyser LT (Qiagen, Valencia, CA, USA) using stainless steel beads in 1 ml STEN buffer supplemented with proteinase inhibitor mix. Tissue lysate was incubated 30 min on ice and centrifuged at 13,000 rpm for 8 min. The supernatant was dialysed in Slide-A-Lyzer Dialysis Cassettes, 7 K MWCO (Thermo Scientific, Waltham, MA, USA) overnight at 4 °C in STEN buffer with one buffer change after 2 hours. Protein concentration measurement and CBS activity assay were performed as in CBS activation assay in cell lysates, except for the addition of 2.5 mM DL-propargylglycine (Sigma-Aldrich, St. Louis, MO, USA), an irreversible inhibitor of cystathionine gamma-lyase (CSE). 260 μg protein was used in the assay and the incubation time was 90 min. Data were normalized to the reaction mixture containing water instead of liver lysate.

2.11. Statistical analysis

Unpaired Student's *t*-test, one-way ANOVA followed by Tukey test, and Kruskal Wallies test followed by Nemenyi test were used to analyse differences in CBS activity in the liver, CBS activation, and sulfide levels in blood, respectively. A *p*-value of < 0.05 was considered to indicate statistical significance.

3. Results

3.1. Low blood sulfide levels in long-lived species

Using extractive alkylation with a bis-pentafluorobenzyl derivative we quantified sulfide concentration in whole blood of naked mole-rat, two other mole-rat species (*F. mechowii*, *F. micklemi*), mouse, guinea pig, and human. Sulfide levels differ significantly between species with human and naked mole-rat exhibiting the lowest values (Fig. 2A). Surprisingly, we found a negative correlation between maximum longevity residual and mean sulfide concentration in blood (Fig. 2B).

3.2. Low endogenous CBS activity in the naked mole-rat liver

Next, we compared endogenous CBS activity in the liver of naked mole-rat and mouse using H₂S-specific probe 7-azido-4-methylcoumarin (AzMC). We observed that H₂S producing activity of CBS is lower in naked mole-rat liver as compared to mouse (Fig. 3).

3.3. Substitution of a conserved cysteine to leucine in naked mole-rat CBS does not affect activation

As CBS is a significant contributor to endogenous H₂S production in mice [11] we screened the naked mole-rat CBS gene for signs of positive selection but failed (File S1). We noticed, however, in the regulatory domain at amino acid position 412 a cysteine > leucine substitution (C412L) present also in CBS from *F. mechowii* and *F. micklemi*. Cysteine at this position is conserved among all other analyzed vertebrates (Fig. 4). Notably in human CBS, the conversion of the corresponding cysteine to serine (C431S) creates a constitutively active form of the enzyme [22]. We, therefore, tested whether substitution of the conserved cysteine to leucine in the regulatory domain of naked mole-rat CBS affects the degree of activation of the enzyme in the presence of SAM. To this end, plasmids encoding either canonical or *in vitro* mutated human or naked mole-rat CBS were transfected into HCT116 human colorectal carcinoma cell line. One of the main criteria for the cell line to be used in this study was its lack of endogenous CBS expression, which – if present-would create a

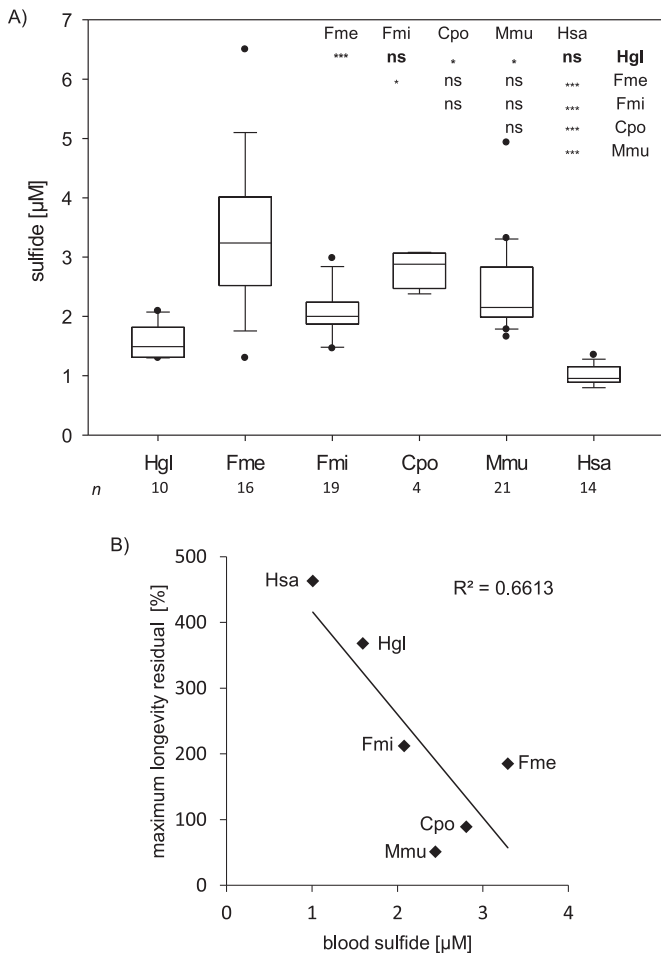


Fig. 2. Sulfide concentration in blood. (A) Sulfide concentration in blood. p -value: * < 0.05, ** < 0.01, *** < 0.001, ns – not significant (Kruskal Wallies test followed by Nemenyi test). (B) Corellation between maximum longevity residual and mean sulfide concentration in blood. In (A) and (B) Hgl – *H. glaber*, Fmi – *F. micklei*, Fme – *F. mechowii*, Cpo – *C. porcellus*, Mmu – *M. musculus*, Hsa – *H. sapiens*.

background signal in the assay. Zhang et al. described HCT116 cells as being CBS mRNA free [23]. In contrast, Yamamoto et al. [24] and Szabo et al. [25] reported low and high CBS expression, respectively. In light of this contradiction, we performed RT-PCR and RNA-seq which confirmed that the transsulfuration pathway in HCT116 cells is suppressed (no CBS and negligible CTH transcripts detectable) (File S2). H₂S-producing CBS activity was tested in cell lysates with the use of AzMC in the presence and in the absence of SAM. Conversion of leucine at position 412 to cysteine in naked mole-rat CBS did not affect enzyme activation (Fig. 5A). Similarly, mutation of the corresponding cysteine to leucine in human CBS did not show any effect. Mutation to serine resulted in a constitutively active enzyme in both species, which is in agreement with published data [22].

3.4. Strong activation of naked mole-rat CBS by SAM

The described experiment, however, revealed that the SAM activation level of naked mole-rat CBS (4-fold) is nearly doubled compared to human CBS (2.3-fold). CBS from *F. mechowii*, *F. micklei*, and mouse show intermediate degree of activation (Fig. 5C).

To test whether the regulatory domain is responsible for the high activation of naked mole-rat CBS we exchanged regulatory domains between human and naked mole-rat CBS. While naked mole-rat CBS activation is not influenced by the presence of

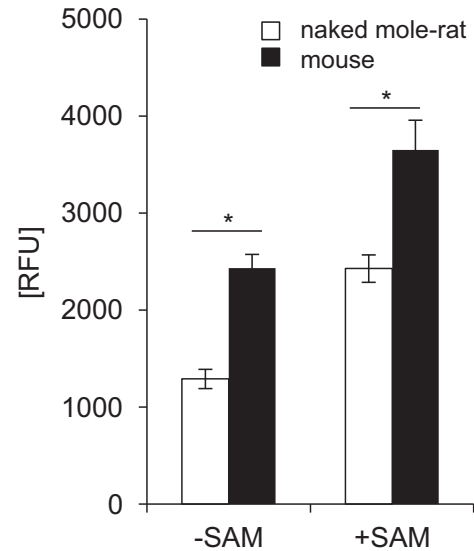


Fig. 3. CBS activity in the liver. Data represent mean \pm SD of 8 animals. Data was normalized to water control (water instead of lysate in the reaction mixture), RFU – relative fluorescence unit. p -value: * < 0.05 (unpaired Student's t -test).

<i>Heterocephalus glaber</i>	APLTVLPTVTL LE HTIAILREK
<i>Fukomys mechowii</i>	APLTVLPSVTL LE HTIAILREK
<i>Fukomys micklei</i>	APLTVLPSVTL LE HTIAILREK
<i>Cavia porcellus</i>	APLTVLPTIT CG HTIAILREK
<i>Mus musculus</i>	APLTVLPTVTL CE DTIAILREK
<i>Rattus norvegicus</i>	APLTVLPTVTL CE HTIAILREK
<i>Cricetulus griseus</i>	APLTVLPTVTL CE HTITILREK
<i>Homo sapiens</i>	APLTVLPTIT CG HTIEILREK
<i>Macaca fascicularis</i>	APLTVLPTV VS CEHTIEILREK
<i>Camelus ferus</i>	APLTVLPTVTL CE HTIEILREK
<i>Bos taurus</i>	APLTVLPTVTL CE HTIEILREK
<i>Fulmarus glacialis</i>	APLTVLPTVTL CAN TVEILREK
<i>Eurypyga helias</i>	APLTVLPTVTL CAN TVEILREK
<i>Ophiophagus hannah</i>	APLTVLPSVTL CE KTIEILKEK
<i>Xenopus laevis</i>	APLTVLPTV SC GQTIQLLREK
<i>Tachysurus vachellii</i>	APLTVLPTVTL CQ KTIKILKEK
<i>Danio rerio</i>	APLTVLPTVTL CQ KTIKILKDK

Fig. 4. Multi-species alignment of sequences flanking the conserved cysteine residue in CBS regulatory domain. The alignment region corresponds to position 426–446 of the alignment in File S1.

human regulatory domain, human CBS core with naked mole-rat regulatory domain shows a 42% decrease in activation (Fig. 5B). This suggests that the cause for a high degree of activation of naked mole-rat CBS lies outside of the regulatory domain.

4. Discussion

The data presented in this study reveal an intriguing negative correlation between blood sulfide levels and maximum longevity residual. In the light of reported increase of transsulfuration activity and high H₂S levels in diet-induced longevity models [5,6],

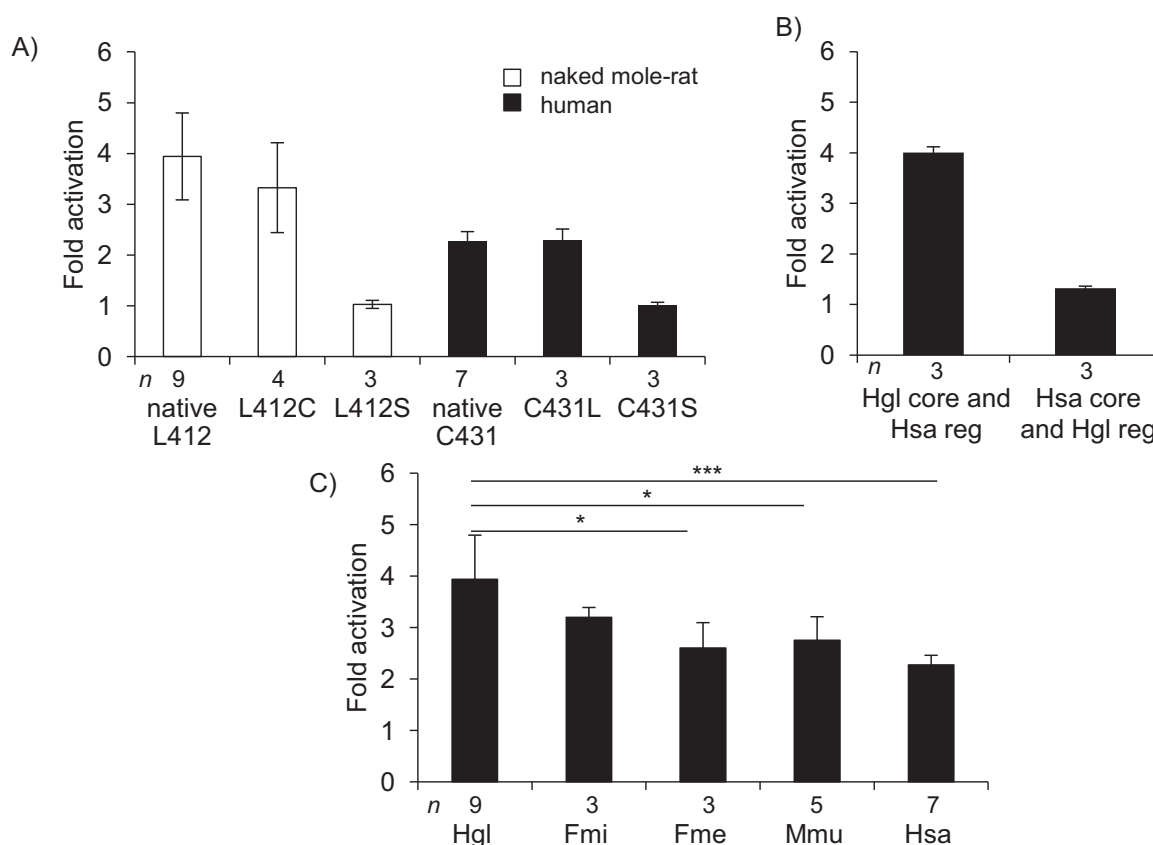


Fig. 5. Activation of CBS by SAM. (A) Fold activation after HCT116 transfection with expression vectors containing either the naked mole-rat CDS with leucine, cysteine and serine at position 412 (native L412, L412C and L412S, respectively) or the human CDS with cysteine, leucine and serine at position 431 (native C431, C431L and C431S, respectively). (B) Fold activation after HCT116 transfection with expression vectors coding for chimeric CBS: naked mole-rat N-terminal heme binding and catalytic domain, and human regulatory domain (Hgl core and Hsa reg) and vice versa (Hsa core and Hgl reg). (C) Fold activation of CBS from different species. Hgl – *H. glaber*, Fmi-*F. micklei*, Fme – *F. mechowii*, Mmu – *M. musculus*, Hsa – *H. sapiens*. In (A) (B) (C), data represent mean \pm SD of *n* biological replicates, *p*-value: * < 0.05, ** < 0.01, *** < 0.001 (one-way ANOVA followed by Tukey test). Data were normalized to the lysate from mock transfected cells.

this observation is unexpected and suggests that the role of H₂S in natural and diet-induced longevity is different.

Given the plethora of reported H₂S effects, this finding is difficult to interpret. H₂S is elevated in cardiovascular [26] and rheumatic disease [27], which suggests that the low sulfide levels may be beneficial. In addition, low CBS activity and low sulfide levels in naked mole-rat may contribute to cancer resistance in this species, as it has been shown that H₂S is promoting both tumor growth and vascularisation [28]. However, the vast majority of studies report beneficial effects of increased H₂S levels and most translational approaches aim to develop H₂S-delivering therapeutics [1].

The low sulfide concentration in naked mole-rat blood is consistent with our findings that H₂S producing activity of CBS is lower in naked mole-rat as compared to mouse. Naked mole-rats feed on the underground parts of plants. Roots and tubers show very low methionine content [29]. Therefore we hypothesize that naked mole-rat diet is low in methionine. This was also pointed out by Buffenstein [30]. Methionine restriction is one of the most powerful dietary regimens resulting in longer lifespan [31]. Interestingly, it has been reported that methionine restriction leads to a decrease in CBS protein levels [2]. Hence, low CBS activity in the naked mole-rat liver may be an adaptation to a low methionine diet. The described features of naked mole-rat CBS may be beneficial under conditions of limited methionine availability. Namely, low basal CBS activity allows for remethylation of homocysteine in order to maintain sufficient methionine levels. However, in case of methionine surplus, a high degree of CBS activation by SAM efficiently directs toxic homocysteine to degradation by the

transsulfuration pathway. Consistently with our hypothesis, isocaloric protein restriction in rats results in increased remethylation of homocysteine to methionine and decrease in CBS activity [7]. Because of unknown specificity and affinity of commercially available anti-CBS antibodies against naked mole-rat CBS, we were not able to compare basal activity and the amount of CBS in the liver across species. This must be acknowledged as a limitation of the study.

Naked mole-rat single amino acid changes are used to explain its phenotype [32, 33]. In the interspecies CBS sequence comparison, we found a mole-rat specific substitution of a conserved cysteine with leucine in the CBS regulatory domain. The amino acid change was potentially interesting given the results of mutagenesis of a corresponding cysteine in the human CBS [22]. Since examples of misleading conclusions on the role of naked mole-rat-specific amino acid changes based on sequence comparisons were already elucidated [34], we experimentally studied the functional consequences of the observed substitution and found that it has no effect on the CBS activation.

However, this experiment revealed a strong activation of naked mole-rat CBS in response to SAM. While in our experiments human CBS show an activation of 2.3 fold, in the literature values ranging from 2 to 5-fold can be found [2,35]. This discrepancy can be explained by the fact that SAM binding to CBS is considerably affected by surface electrostatics [35]. Nevertheless, under normalized conditions used in this study (the same cell line transfected with CBS from different species under the control of identical promoters) naked mole-rat CBS shows consistently a higher degree of activation by SAM than human, mouse, and *F. mechowii* CBS.

CBS activity substantially affects plasma homocysteine levels [36,37]. Since hyperhomocysteinemia is observed in many age-related diseases [38] and is a strong predictor of mortality among individuals with coronary artery disease [39], further characterization and kinetic studies of naked mole-rat CBS may shed new light on the mechanisms underlying the extremely long health-span of this species.

In summary, we found a negative correlation between blood sulfide concentration and maximum longevity residual and provide the first insights into naked mole-rat transsulfuration pathway. We report low H₂S producing CBS activity in the naked mole-rat liver and a high activation of naked mole-rat CBS by SAM. In addition, we determined that the substitution of the conserved cysteine (C412L) in the regulatory domain of naked mole-rat CBS does not affect the degree of activation of the enzyme. The described features of naked mole-rat CBS call for detailed research on naked mole-rat transsulfuration pathway.

Acknowledgments

We thank Ralf A. Claus and Marcel Kramer for providing mouse samples and Jacqueline Fischer for excellent technical assistance. We would also like to thank Paul Van Daele for providing *F. micklemi* used in this study. This work was supported by grants from the Leibniz Association to TH and MP (WGL, SAW-2012-FLI-2) and the German Research Foundation DFG to PD (DA 992/3-1) and MP (PL 173/8-1).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.redox.2016.01.008>.

References

- [1] J.L. Wallace, R. Wang, Hydrogen sulfide-based therapeutics: exploiting a unique but ubiquitous gasotransmitter, *Nat. Rev. Drug. Discov.* 14 (2015) 329–345.
- [2] A. Prudova, Z. Bauman, A. Braun, V. Vitvitsky, S.C. Lu, et al., S-adenosylmethionine stabilizes cystathionine beta-synthase and modulates redox capacity, *Proc. Natl. Acad. Sci. USA* 103 (2006) 6489–6494.
- [3] J.D. Finkelstein, W.E. Kyle, J.L. Martin, A.M. Pick, Activation of cystathionine synthase by adenosylmethionine and adenosylethionine, *Biochem. Biophys. Res. Commun.* 66 (1975) 81–87.
- [4] D.L. Miller, M.B. Roth, Hydrogen sulfide increases thermotolerance and life-span in *Caenorhabditis elegans*, *Proc. Natl. Acad. Sci. USA* 104 (2007) 20618–20622.
- [5] H. Kabil, O. Kabil, R. Banerjee, L.G. Harshman, S.D. Pletcher, Increased transsulfuration mediates longevity and dietary restriction in *Drosophila*, *Proc. Natl. Acad. Sci. USA* 108 (2011) 16831–16836.
- [6] C. Hine, E. Harputlugil, Y. Zhang, C. Ruckenstuhl, B.C. Lee, et al., Endogenous hydrogen sulfide production is essential for dietary restriction benefits, *Cell* 160 (2015) 132–144.
- [7] S.C. Kalhan, S.O. Uppal, J.L. Moorman, C. Bennett, L.L. Gruca, et al., Metabolic and genomic response to dietary isocaloric protein restriction in the rat, *J. Biol. Chem.* 286 (2011) 5266–5277.
- [8] J.P. de Magalhães, J. Costa, G.M. Church, An analysis of the relationship between metabolism, developmental schedules, and longevity using phylogenetic independent contrasts, *J. Gerontol. A Biol. Sci. Med. Sci.* 62 (2007) 149–160.
- [9] R. Buffenstein, Negligible senescence in the longest living rodent, the naked mole-rat: insights from a successfully aging species, *J. Comp. Physiol. B* 178 (2008) 439–445.
- [10] S. Liang, J. Mele, Y. Wu, R. Buffenstein, P.J. Hornsby, Resistance to experimental tumorigenesis in cells of a long-lived mammal, the naked mole-rat (*Heterocephalus glaber*), *Aging Cell.* 9 (2010) 626–635.
- [11] K.K. Jensen, N.S. Geoghagen, L. Jin, T.G. Holt, Q. Luo, et al., Pharmacological activation and genetic manipulation of cystathionine beta-synthase alter circulating levels of homocysteine and hydrogen sulfide in mice, *Eur. J. Pharmacol.* 650 (2011) 86–93.
- [12] O. McCook, P. Radermacher, C. Volani, P. Asfar, A. Ignatius, et al., H₂S during circulatory shock: some unresolved questions, *Nitric Oxide* 41 (2014) 48–61.
- [13] P.A.A.G. Van Daele, P. Dammann, J.L. Meier, M. Kawaliika, C. Van De Woestijne, et al., Chromosomal diversity in mole-rats of the genus *Cryptomys* (Rodentia: Bathyergidae) from the Zambezi region: with descriptions of new karyotypes, *J. Zool. Lond.* 264 (2004) 317–326.
- [14] P.A. Van Daele, E. Verheyen, M. Brunain, D. Adriaens, Cytochrome b sequence analysis reveals differential molecular evolution in African mole-rats of the chromosomally hyperdiverse genus *Fukomys* (Bathyergidae, Rodentia) from the Zambezi region, *Mol. Phylogenet. Evol.* 45 (2007) 142–157.
- [15] K. Pruitt, G. Brown, T. Tatusova, D. Maglott, Chapter 18 the reference sequence (RefSeq) database, in: J. McEntyre, J. Ostell (Eds.), *The NCBI Handbook* [Internet], National Center for Biotechnology Information (US), Bethesda (MD), 2002.
- [16] C. Trapnell, L. Pachter, S.L. Salzberg, TopHat: discovering splice junctions with RNA-Seq, *Bioinformatics* 25 (2009) 1105–1111.
- [17] S. Anders, P.T. Pyl, W. Huber, HTSeq – a Python framework to work with high-throughput sequencing data, *Bioinformatics* 31 (2015) 166–169.
- [18] A. Loytynoja, N. Goldman, Phylogeny-aware gap placement prevents errors in sequence alignment and evolutionary analysis, *Science* 320 (2008) 1632–1635.
- [19] G. Talavera, J. Castresana, Improvement of phylogenies after removing divergent and ambiguously aligned blocks from protein sequence alignments, *Syst. Biol.* 56 (2007) 564–577.
- [20] Z. Yang, PAML 4: phylogenetic analysis by maximum likelihood, *Mol. Biol. Evol.* 24 (2007) 1586–1591.
- [21] M.K. Thorson, T. Majtan, J.P. Kraus, A.M. Barrios, Identification of cystathionine beta-synthase inhibitors using a hydrogen sulfide selective probe, *Angew. Chem. Int. Ed. Engl.* 52 (2013) 4641–4644.
- [22] N. Frank, V. Kery, K.N. Maclean, J.P. Kraus, Solvent-accessible cysteines in human cystathionine beta-synthase: crucial role of cysteine 431 in S-adenosyl-L-methionine binding, *Biochemistry* 45 (2006) 11021–11029.
- [23] W. Zhang, A. Braun, Z. Bauman, H. Olteanu, P. Madzellan, et al., Expression profiling of homocysteine junction enzymes in the NCI60 panel of human cancer cell lines, *Cancer Res.* 65 (2005) 1554–1560.
- [24] T. Yamamoto, N. Takano, K. Ishiwata, M. Ohmura, Y. Nagahata, et al., Reduced methylation of PFKFB3 in cancer cells shunts glucose towards the pentose phosphate pathway, *Nat. Commun.* 5 (2014) 3480.
- [25] C. Szabo, C. Coletta, C. Chao, K. Modis, B. Szczesny, et al., Tumor-derived hydrogen sulfide, produced by cystathionine-beta-synthase, stimulates bioenergetics, cell proliferation, and angiogenesis in colon cancer, *Proc. Natl. Acad. Sci. USA* 110 (2013) 12474–12479.
- [26] E.A. Peter, X. Shen, S.H. Shah, S. Pardue, J.D. Glawe, et al., Plasma free H₂S levels are elevated in patients with cardiovascular disease, *J. Am. Heart Assoc.* 2 (2013) e000387.
- [27] N. Muniraj, L.K. Stamp, A. Badieli, A. Hegde, V. Cameron, et al., Hydrogen sulfide acts as a pro-inflammatory mediator in rheumatic disease, *Int. J. Rheum. Dis.* (2014).
- [28] M.R. Hellmich, C. Coletta, C. Chao, C. Szabo, The therapeutic potential of cystathionine beta-synthetase/hydrogen sulfide inhibition in cancer, *Antioxid. Redox Signal* 22 (2015) 424–448.
- [29] Y. Ingenbleek, The nutritional relationship linking sulfur to nitrogen in living organisms, *J. Nutr.* 136 (2006) 1641S–1651S.
- [30] G.P. Ables, H.M. Brown-Borg, R. Buffenstein, C.D. Church, A.K. Elshorbagy, et al., The first international mini-symposium on methionine restriction and lifespan, *Front. Genet.* 5 (2014) 122.
- [31] N. Orentreich, J.R. Matias, A. DeFelice, J.A. Zimmerman, Low methionine ingestion by rats extends life span, *J. Nutr.* 123 (1993) 269–274.
- [32] Z. Yang, Y. Zhang, L. Chen, Single amino acid changes in naked mole rat may reveal new anti-cancer mechanisms in mammals, *Gene* 572 (2015) 101–107.
- [33] E.B. Kim, X. Fang, A.A. Fushan, Z. Huang, A.V. Lobanov, et al., Genome sequencing reveals insights into physiology and longevity of the naked mole rat, *Nature* 479 (2011) 223–227.
- [34] F. Delsuc, M.K. Tilak, Naked but not Hairless: the pitfalls of analyses of molecular adaptation based on few genome sequence comparisons, *Genome Biol. Evol.* 7 (2015) 768–774.
- [35] A.L. Pey, T. Majtan, J.P. Kraus, The role of surface electrostatics on the stability, function and regulation of human cystathionine beta-synthase, a complex multidomain and oligomeric protein, *Biochim. Biophys. Acta* 1844 (2014) 1453–1462.
- [36] L. Wang, K.H. Jhee, X. Hua, P.M. DiBello, D.W. Jacobsen, et al., Modulation of cystathionine beta-synthase level regulates total serum homocysteine in mice, *Circ. Res.* 94 (2004) 1318–1324.
- [37] M. Watanabe, J. Osada, Y. Aratani, K. Kluckman, R. Reddick, et al., Mice deficient in cystathionine beta-synthase: animal models for mild and severe homocyst(e)inemia, *Proc. Natl. Acad. Sci. USA* 92 (1995) 1585–1589.
- [38] H.K. Kuo, F.A. Sorond, J.H. Chen, A. Hashmi, W.P. Milberg, et al., The role of homocysteine in multisystem age-related problems: a systematic review, *J. Gerontol. A Biol. Sci. Med. Sci.* 60 (2005) 1190–1201.
- [39] O. Nygard, J.E. Nordrehaug, H. Refsum, P.M. Ueland, M. Farstad, et al., Plasma homocysteine levels and mortality in patients with coronary artery disease, *N Engl. J. Med.* 337 (1997) 230–236.