Table 5 The molecular pathway relevant to MS brain-lesion proteome suggested by Ingenuity pathway analysis (IPA) search

Stage	Rank	Functional category	The number of genes classified	*P*-value
AP	1	Calcium signaling	7	2,53E-03
	2	Oxidative phosphorylation	4	2,69E-02
CAP	1	Calcium signaling	14	5,14E-04
	2	Hepatic fibrosis and hepatic stellate cell activation	11	1,53E-03
	3	Purine metabolism	16	3,05E-03
	4	Actin cytoskeleton signaling	13	5,77E-03
	5	Oxidative phosphorylation	9	1,12E-02
CP	1	Biosynthesis of steroids	4	7,37E-04
	2	Actin cytoskeleton signaling	8	8,00E-03
	3	Ubiquinone biosynthesis	4	9,54E-03
	4	Axonal guidance signaling	11	1,37E-02
	5	Integrin signaling	7	2,19E-02

The list of Entrez Gene IDs of MS brain-lesion proteome was uploaded onto the 'Core Analysis' tool of IPA. The canonical pathways relevant to the proteome data are shown with the number of genes classified and *P*-value.
Abbreviations: AP, acute plaques; CAP, chronic active plaques; and CP, chronic plaques.

the ECM and integrin signaling pathway to CAP and CP was further verified by molecular network analysis using PANTHER, KeyMolnet, and IPA followed by statistical evaluation. These *in silico* observations agree well with *in-vivo* studies, showing remarkable upregulation of diverse ECM constituents in MS brain lesions, where cytokine/chemokine-activated microglia, astrocytes, and infiltrating macrophages release a large amount of proteolytic enzymes bound to ECM molecules, which mediate myelin breakdown [17,18]. Glial scars in chronic lesions of MS include certain ECM proteins that contribute to the failure of regeneration of damaged axons and remyelination of preserved axons [17,18].

In active demyelinating lesions of MS, the expression of vitronectin is greatly enhanced in blood vessel walls, as well as in demyelinated axons and hypertrophic astrocytes at the edge of demyelination [19]. The levels of CD51, a vitronectin receptor, are elevated in the serum of relapsing-remitting MS patients [20]. Vitronectin promotes migration of reactive astrocytes expressing αvβ8 integrin [21]. In active demyelinating lesions of MS, fibronectin is accumulated in the brain parenchyma and is deposited abundantly in blood vessel walls and perivascular infiltrates [22]. Fibronectin facilitates migration of immune cells, promotes proliferation of astrocytes, and inhibits differentiation of oligodendrocyte progenitors [23]. In MS lesions, both vitronectin and fibronectin are derived mainly form plasma protein components passing across the disrupted blood–brain barrier and partly from the local synthesis by endothelial cells, macrophages, astrocytes, and infiltrating immune cells. Vitronectin and fibronectin activate microglia and upregulate MMP-9 production [24]. Thrombospondin produced by reactive astrocytes facilitates macrophage-mediated phagocytosis of apoptotic cells and possible uptake of degraded myelin via the ECM receptors CD36 and αvβ3 integrin [25]. Large-scale sequencing of MS plaque cDNA libraries showed that osteopontin (SPP1), a proinflammatory component of ECM, is one of the most abundant transcripts [26]. The clinical severity of EAE is attenuated in SPP1-deficient mice [26]. The expression of osteopontin is enhanced in astrocytes in active demyelinating lesions of MS [27]. The plasma osteopontin levels are elevated in active relapsing-remitting MS patients [28]. All of these observations support the concept that the selective blockade of the interaction between ECM and integrins in brain lesions *in situ* would be a target candidate for therapeutic intervention in MS.

Because focal adhesion kinase (FAK) is a central mediator of the integrin signaling pathway (see Figure 1), one possible choice is the use of an inhibitor for ECM-induced autophosphorylation of FAK [29]. TAE226, a FAK inhibitor, suppresses tumor cell invasion *in vivo* [29]. Another option for integrin signaling inhibitors is disintegrins, a group of small disulfide-rich peptides containing the arginine–glycine–aspartic acid sequence that mediates the selective binding to integrins [30]. Liposomal delivery of contortrostatin, a snake venome disintegrin, shows a tumor-suppressive anti-angiogenic activity [30]. However, a complete blockade of general function of integrins has a risk for inducing serious side effects [31]. Even in the context of the selective blockade, treatment with a humanized monoclonal antibody against VLA4, α4β1 integrin (natalizumab) reduced relapses 66% in clinical trials of MS but also activated the lethal infection of JC virus in some patients [32].

Acknowledgments

This work was supported by grants to J-IS from Research on Psychiatric and Neurological Diseases and Mental Health, the Ministry of Health, Labour and Welfare of Japan (H17-020), Research on Health Sciences Focusing on Drug Innovation, the Japan Health Sciences Foundation (KH21101), the Grant-in-Aid for Scientific Research, the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) (B18300118), the High-Tech Research Center Project, MEXT (S0801043) and from the Nakatomi Foundation.

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Disease Markers 27 (2009) 239–252
DOI 10.3233/DMA-2009-0670
IOS Press

Molecular network analysis suggests aberrant CREB-mediated gene regulation in the Alzheimer disease hippocampus

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Abstract. The pathogenesis of Alzheimer disease (AD) involves the complex interaction between genetic and environmental factors affecting multiple cellular pathways. Recent advances in systems biology provide a system-level understanding of AD by elucidating the genome-wide molecular interactions. By using KeyMolnet, a bioinformatics tool for analyzing molecular interactions on the curated knowledgebase, we characterized molecular network of 2,883 all stages of AD-related genes (ADGs) and 559 incipient AD-related genes (IADGs) identified by global gene expression profiling of the hippocampal CA1 region of AD brains in terms of significant clinical and pathological correlations (Blalock et al., Proc Natl Acad Sci USA 101: 2173-2178, 2004). By the common upstream search, KeyMolnet identified cAMP-response element-binding protein (CREB) as the principal transcription factor exhibiting the most significant relevance to molecular networks of both ADGs and IADGs. The CREB-regulated transcriptional network included upregulated and downregulated sets of ADGs and IADGs, suggesting an involvement of generalized deregulation of the CREB signaling pathway in the pathophysiology of AD, beginning at the early stage of the disease. To verify the *in silico* observations *in vivo*, we conducted immunohistochemical studies of 11 AD and 13 age-matched control brains by using anti-phoshorylated CREB (pCREB) antibody. An abnormal accumulation of pCREB imunoreactivity was identified in granules of granulovacuolar degeneration (GVD) in the hippocampal neurons of AD brains. These observations suggest that aberrant CREB-mediated gene regulation serves as a molecular biomarker of AD-related pathological processes, and support the hypothesis that sequestration of pCREB in GVD granules is in part responsible for deregulation of CREB-mediated gene expression in AD hippocampus.

Keywords: Alzheimer disease, CREB, granulovacuolar degeneration, keymolnet, molecular network, systems biology

1. Introduction

Alzheimer disease (AD) is the most common cause of dementia worldwide, affecting the elderly population, characterized by the hallmark pathology of amyloid-β (Aβ) deposition and neurofibrillary tangle (NFT) formation in the brain. The complex interaction between genetic and environmental factors affecting multiple cellular pathways plays a role in the pathogenesis of AD [1]. The completion of the Human Genome Project in 2003 allows us to systematically characterize the comprehensive disease-associated profiles of the whole human genome. It promotes us to identify disease-specific and stage-specific molecular signatures and biomarkers for diagnosis and prediction of prognosis, and druggable targets for therapy [2]. Actually, global transcriptome analysis of AD brains identified a battery of genes aberrantly regulated in AD, whose role has not been previously

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ISSN 0278-0240/09/$17.00

predicted in its pathogenesis. They include reduced expression of kinases/phosphatases, cytoskeletal proteins, synaptic proteins, and neurotransmitter receptors in NFT-bearing CA1 neurons [3], downregulaton of neurotrophic factors and upregulation of proapoptotic molecules in the hippocampal CA1 region [4], disturbed sphingolipid metabolism in various brain regions during progression of AD [5], and overexpression of the AMPA receptor GluR2 subunit in synaptosomes of prefrontal cortex [6]. However, in global expression analysis, the important biological implications are often left behind to be characterized, because the huge amount of high-density microarray data is highly complex. Furthermore, cardinal observations obtained from *in silico* data analysis should be validated by independent wet lab experiments.

Recent advances in systems biology enable us to illustrate a cell-wide map of the complex molecular interactions with aid of the literature-based knowledgebase of molecular pathways [7,8]. In the scale-free molecular network, targeted disruption of several critical components, on which the biologically important molecular connections concentrate, could disturb the whole cellular function by destabilizing the network [9]. Thus, molecular network analysis goes beyond gene-by-gene analysis to shed light on a system-level understanding of molecular relationships among individual genes and networks.

The present study is designed to conduct molecular network analysis of a published microarray dataset of Blalock et al. [10]. It contains genome-wide expression profiling of hippocampal CA1 tissues derived from 22 AD patients with well-defined clinical and pathological stages. They identified 3,413 all stages of AD-related genes (ADGs) and 609 incipient AD-related genes (IADGs), and characterized overrepresented genes by using a bioinformatics tool named Expression Analysis Systematic Explorer (EASE). They found upregulation of tumor suppressors, oligodendrocyte growth factors, and protein kinase A (PKA) modulators, along with downregulation of protein folding/metabolism/transport machinery molecules in incipient AD (IAD) [10]. Recently, a different study followed up analysis of this dataset by weighted gene coexpression network analysis (WGCNA) that calculates a matrix containing all pairwise Pearson correlations between whole microarray probe sets across all subjects in an unsupervised manner. They identified AD-related coexpression modules that play key roles in synaptic transmission, extracellular transport, mitochondrial and metabolic functions, and myelination [11]. However, all of these studies did not clarify the common upstream transcription factors governing molecular networks, closely associated with deregulated gene expression in AD brains. By using KeyMolnet, a bioinformatics tool for analyzing molecular interactions on the curated knowledgebase [12], we characterized the most relevant molecular network of AD brain transcriptome, composed of the genes coordinately regulated by putative common upstream transcription factors.

2. Materials and methods

2.1. The dataset

We performed molecular network analysis of ADGs and IADGs, derived from a dataset of Blalock et al. [10]. It contains gene expression profiling of frozen tissues of the CA1 hippocampus, performed by analyzing with the Affymetrix Human Genome HG-U133A chip that contains 22,215 transcripts. The complete dataset is available from Gene Expression Omnibus (GEO) database (GSE1297). RNA was isolated from the samples of 31 age-matched individuals, composed of nine control subjects, seven patients with incipient AD (IAD), eight with moderate AD, and seven with severe AD [10]. The dataset was normalized following the Microarray Analysis Suite 5.0 (MAS5) algorithm. The clinical stage of AD was defined by the Mini-Mental State Examination (MMSE) score, i.e. control (MMSE $>$ 25), incipient AD (MMSE 20–26), moderate AD (MMSE 14–19), and severe AD (MMSE $<$ 14). The neurofibrillary tangle (NFT) burden was determined in each brain sample, which always showed an inverse relationship with the MMSE score. The statistical correlation between the expression levels of individual genes and the MMSE and NFT scores was evaluated by Pearson's correlation tests and ANOVA. With respect to overall correlations across 31 subjects, the study identified 3,413 ADGs, composed of 1,977 upregulated and 1,436 downregulated genes in all stages of AD patients versus control subjects. The study also identified 609 IADGs, composed of 431 upregulated and 178 downregulated genes in IAD patients versus control subjects.

2.2. Gene ID conversion

We converted Affymetrix probe IDs into the corresponding National Center for Biotechnology Information (NCBI) Entrez Gene IDs by using the

Database for Annotation, Visualization and Integrated Discovery (DAVID) 2008 Gene ID conversion tool (david.abcc.ncifcrf.gov) [13]. Then, we excluded a set of non-annotated genes, overlapping genes, and those listed concurrently in both upregulated and downregulated classes.

2.3. Molecular network analysis

KeyMolnet is a comprehensive knowledgebase, originally developed by the Institute of Medicinal Molecular Design (IMMD), Tokyo, Japan [12]. It covers virtually all the relationships heretofore reported among human genes, molecules, diseases, pathways and drugs, whose information is manually collected, carefully curated, and regularly updated by expert biologists. The database is categorized into the core contents collected from selected review articles with the highest reliability, or the secondary contents extracted from abstracts of PubMed database and Human Protein Reference database (HPRD). By importing microarray data, such as the list of Entrez Gene ID and fold changes of individual probes, KeyMolnet automatically provides corresponding molecules as a node on networks.

The common upstream search is a mode of network analysis that extracts the most relevant molecular network composed of the genes coordinately regulated by putative common upstream transcription factors. The generated network was compared side by side with 403 human canonical pathways of the KeyMolnet library. To reduce the potential bias toward the selection of major pathways, all well-established biological pathways covering both major and minor classes were collected by extensive search of valid review articles with journal impact factors greater than 10. Further information on the canonical pathways of KeyMolnet is available from IMMD upon request (www.immd.co.jp/en/keymolnet/index.html). The algorithm counting the number of overlapping molecular relations between the extracted network and the canonical pathway makes it possible to identify the canonical pathway showing the most significant contribution to the extracted network. It is constructed by modification of the algorithm developed for GO::TermFinder [14]. The significance in the similarity between the extracted network and the canonical pathway is scored following the formula, where O = the number of overlapping molecular relations between the extracted network and the canonical pathway, V = the number of molecular relations located in the extracted network, C = the number of molecular relations located in the canonical pathway, T = the number of total molecular relations composed of approximately 110,000 sets, and the X = the sigma variable that defines coincidence.

$$\text{Score} = -\log_2(\text{Score}(p))$$

$$\text{Score}(p) = \sum_{x=O}^{Min(C,V)} f(x)$$

$$f(x) = {}_C C_x \cdot {}_{T-C} C_{V-x} / {}_T C_V$$

2.4. Immunohistochemistry

The autopsied brain samples were provided by Research Resource Network (RRN), Japan. Written informed consent was obtained form all the cases. The Ethics Committee of National Center of Neurology and Psychiatry approved the present study. The study population consists of 11 AD patients composed of five men and six women with the mean age of 71 ± 9 years, and 13 other neurological disease (termed as non-AD) patients composed of six men and seven women with the mean age of 69 ± 9 years. The non-AD cases include three patients with Parkinson disease (PD), two with multiple system atrophy (MSA), four with amyotrophic lateral sclerosis (ALS), and four with myotonic dystrophy. The average of brain weight was 1,038 ± 163 gram in AD cases and 1,195 ± 182 gram in non-AD cases. Brain tissues of the hippocampus and the motor cortex were fixed with 4% paraformaldehyde (PFA), embedded in paraffin, and processed for ten micron-thick serial sections. All AD cases were satisfied with the Consortium to Establish a Registry for Alzheimer's Disease (CERAD) criteria for diagnosis of definite AD [15]. They were categorized into the stage C of amyloid deposition and the stage VI of neurofibrillary degeneration, following the Braak's staging [16].

The immunohistochemistry protocol was described elsewhere [17]. In brief, after deparaffination, tissue sections were heated in 10 mM citrate sodium buffer, pH 6.0 by autoclave at 125°C for 30 sec in a temperature-controlled pressure chamber (Dako, Tokyo, Japan). They were incubated with 3% hydrogen peroxide-containing methanol to block the endogenous peroxidase activity, and with phosphate-buffered saline (PBS) containing 10% normal goat serum (NGS) at room temperature (RT) for 15 min to block non-specific staining. Then, tissue sections were stained at 4°C overnight with rabbit polyclonal anti-phoshorylated cAMP-response element-binding protein (pCREB) an-

tibody at a dilution of 1:1,000 (Y011052; Applied Biological Materials, Richmond, BC, Canada). This antibody was produced against a synthesized phosphopeptide spanning R-P-SP-Y-R, derived from the human CREB1 amino acid sequences surrounding the serine 133 residue (Ser-133), and purified by affinity-chromatography with an epitope-specific phosphopeptide. The specificity of the antibody was verified by western blot analysis of a human neuronal cell line exposed to forskolin in culture (not shown). After several washes, the tissue sections were incubated with horseradish peroxidase (HRP)-conjugated anti-rabbit antibody (Nichirei, Tokyo, Japan), and colorized with DAB substrate (Vector Laboratories, Burlingame, CA, USA), followed by a counterstain with hematoxylin. The adjacent sections were immunolabeled with mouse monoclonal anti-GFAP antibody (Nichirei). For negative controls, the step of incubation with primary antibodies was omitted.

3. Results

3.1. Transcriptome dataset of Alzheimer disease hippocampus

The dataset of Blalock et al. [10] contains genome-wide transcriptome of the hippocampus CA1 region, derived from nine control subjects, seven patients with incipient AD (IAD), eight with moderate AD, and seven with severe AD. They identified 3,413 all stages of AD-related genes (ADGs) and 609 IAD-related genes (IADGs) based on significant clinical and pathological correlations. We performed extensive curation of their data, and extracted 2,883 Entrez Gene IDs of ADGs, composed of 1,675 upregulated and 1,208 downregulated genes in all stages of AD patients versus control subjects (Supplementary Tables 1 and 2 online). We also identified 559 Entrez Gene IDs of IADGs, composed of 395 upregulated and 164 downregulated genes in IAD patients versus control subjects (Supplementary Tables 3 and 4 online).

3.2. The molecular network analysis of ADGs and IADGs identified CREB as a central transcription factor

First, we imported 2,883 Entrez Gene IDs of ADGs, along with the expression levels, into KeyMolnet (the version 4.9.9.616 of July 1, 2009). The common upstream search of the core contents generated a complex network composed of 508 fundamental nodes with 735 molecular relations, arranged with respect to subcellular location of the molecules by the editing function of KeyMolnet (Fig. 1). By statistical evaluation, the extracted network showed the most significant relationship with transcriptional regulation by CREB with the score of 229 and score (p) = 1.141E-069, where CREB is located as a common upstream transcription factor that has direct connections with 50 nodes, all of which are known CRE-responsive genes (Fig. 2 and Table 1). Unexpectedly, the CREB-regulated transcriptional network is comprised of not only 17 upregulated ADGs but also 26 downregulated ADGs. These results suggest not simply either overactivation or hypoactivation of CREB but an involvement of generalized deregulation of the CREB signaling pathway in the pathophysiology of AD. The second rank pathway was transcriptional regulation by nuclear factor kappa B (NF-κB) with the score of 158 and score (p) = 1.945E-048 (Supplementary Fig. 1 online), while the third rank was transcriptional regulation by vitamin D receptor (VDR) with the score of 140 and score (p) = 5.841E-042 (Supplementary Fig. 2 online).

Next, we imported 559 Entrez Gene IDs of IADGs and the expression levels into KeyMolnet. Subsequently, the common upstream search of the core contents generated a less complex network composed of 143 fundamental nodes with 190 molecular relations (Fig. 3). By statistical evaluation, the extracted network showed again the most significant relationship with transcriptional regulation by CREB with the score of 71 and score (p) = 3.325E-022, comprised of 5 upregulated and 5 downregulated IADGs (Fig. 4 and Table 1). These results suggest that functional impairment of CREB in the AD hippocampus is beginning at the early stage of the disease. The second rank pathway was transcriptional regulation by NF-κB or by glucocorticoid receptor (GR) with the identical score of 53 and score (p) = 1.163E-016 between both.

3.3. Granulovacuolar degeneration in hippocampal neurons of AD brains expressed pCREB immunoreactivity

It is well known that a wide range of extracellular stimuli activates CREB by inducing phosphorylation of Ser-133 on CREB, thereby it functions as a transcriptional activator [18,19]. Because the molecular network of both ADGs and IADGs reflects persistent impairment of CREB function in the AD hippocampus, we studied the expression of Ser-133-phosphorylated

Table 1
The list of 51 genes constructing the CREB-regulated transcriptional network in AD hippocampus

KeyMolnet symbol	Gene name	Upregulation or downregulation[a]	Involvement in IAD network	Swiss-Prot ID
14-3-3epsilon	14-3-3 protein epsilon	down		P62258
AChE	acetylcholinestrase	down		P22303
AhR	arylhydrocarbon receptor	km		P35869
BCKDH	branched-chain alpha-keto acid dehydrogenase	down		P09622, P11182, P12694, P21953
Bcl-2	B-cell lymphoma 2	up		P10415
BiP	78 kDa glucose-regulated protein	down	yes	P11021
BRCA1	breast cancer type 1 susceptibility protein	up		P38398
C/EBPb	CCAAT/enhancer binding protein beta	km	yes	P17676
CCK	cholecystokinin	down		P06307
CDK5	cyclin dependent kinase 5	down		Q00535
ChromograninA	chromogranin A	down		P10645
CPT	carnitine palmitoyl transferase	up	yes	P50416, Q92523, Q8TCG5, P23786
CREB	cAMP-response-element-binding-protein	km	yes	P16220
CRF	corticotropin-releasing factor	down	yes	P06850
cyclinA	cyclin A	down		P78396, P20248
cyto-c	cytochrome c	down		P99999
DIO2	type II iodothyronine deiodinase	down		Q92813
Egr1	early growth response protein 1	up		P18146
ENO2	neuron-specific enolase	down		P09104
FN1	fibronectin 1	down		P02751
GADD34	protein phosphatase 1, regulatory subunit 15A	up		O75807
GluR1	glutamate receptor 1	down		P42261
GR	glucocorticoid receptor	km	yes	P04150
GS	glutamine synthetase	down	yes	P15104
HO-1	heme oxygenase 1	up		P09601
ICAM-1	intercellular adhesion molecule 1	up		P05362
IGF1	insulin-like growth factor 1	down		P01343, P05019
IL-6	interleukin-6	up		P05231
JunD	transcription factor Jun-D	up	yes	P17535
LDH	L-lactate dehydrogenase	down		Q6ZMR3, Q9BYZ2, P00338, P07195, P07864
MITF	microphthalmia-associated transcription factor	up	yes	O75030
MnSOD	manganese superoxide dismutase	up		P04179
NF-L	neurofilament triplet L protein	down		P07196
NPY	neuropeptide Y	down		P01303
NR4A2	orphan nuclear receptor NR4A2	km		P43354
ODC	ornithine decarboxylase	up		P11926
PC	prohormone convertase	down		P29120, P16519, Q16549
PCB	pyruvate carboxylase	up	yes	P11498
PCNA	proliferating cell nuclear antigen	down		P12004
PER1	period circadian protein 1	up	yes	O15534
PER2	period circadian protein 2	up		O15055
Pit-1	pituitary-specific positive transcription factor 1	km	yes	P28069
PPT-A	preprotachykinin A	down	yes	P20366
proenkeph	proenkephalin	down		P01213, P01210
SGK	serum- and glucocorticoid-inducible kinase	up	yes	O00141, Q9HBY8, Q96BR1
SST	somatostatin	down	yes	P61278
STAT3	signal transducer and activator of transcription 3	km	yes	P40763
SynapsinI	synapsin-1	down		P17600
TGFb2	transforming growth factor beta 2	up		P61812
TyrAT	tyrosine aminotransferase	up		P17735
VIP	vasoactive intestinal peptide	down		P01282

Km represents additional nodes unlisted in the original set of 2,883 ADGs but automatically incorporated from KeyMolnet core contents following the network-searching algorithm.

CREB (pCREB) in 11 AD and 13 age-matched control brains by immunohistochemistry. The granular components of granulovacuolar degeneration (GVD), accumulated in the cytoplasm of hippocampal pyramidal neurons in both AD and non-AD brains, expressed strong immunoreactivity against pCREB (Fig. 5, panels a-d). However, the nuclei of hippocampal pyramidal neurons were devoid of pCREB immunoreac-

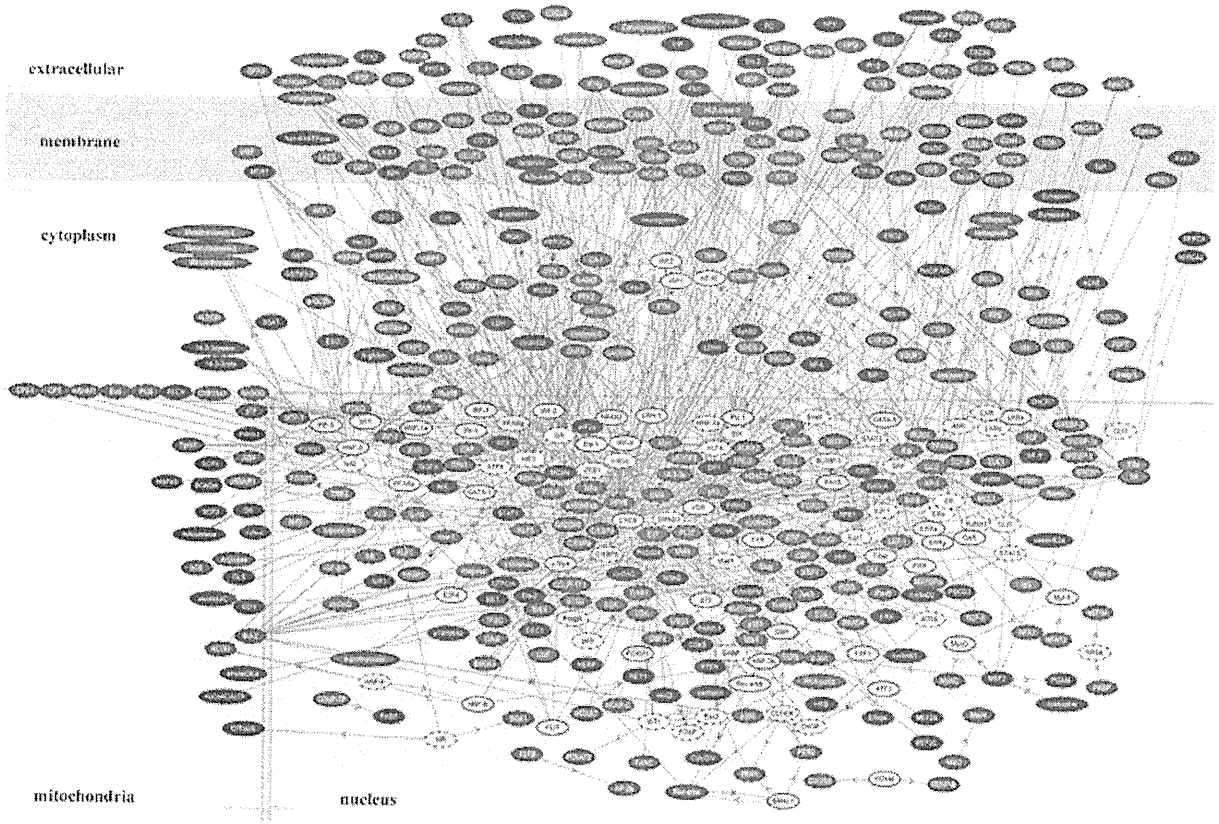

Fig. 1. Molecular network of all stages of AD-related genes (ADGs). The list of 2,883 Entrez Gene IDs corresponding to ADGs was imported into KeyMolnet. The common upstream search of the core contents generated a network composed of 508 fundamental nodes with 735 molecular relations, arranged with respect to subcellular location of the molecules. Red nodes represent upregulated genes, whereas blue nodes represent downregulated genes. White nodes exhibit additional nodes extracted automatically from the core contents incorporated in the network to establish molecular connections. The direction of molecular relation is indicated by red-colored dash line with arrow (transcriptional activation) or blue-colored dash line with arrow and stop (transcriptional repression).

tivity. In addition, the vacuolar component of GVD lacked pCREB immunoreactivity, while neuritic processes of hippocampal neurons expressed variable levels of pCREB immunoreactivity (Fig. 5, panel c). pCREB-immunoreactive GVD-bearing neurons were distributed chiefly in the CA1-CA3 sectors. Senile plaques and neurofibrillary tangles were completely devoid of pCREB immunolabeling. Although the number of pCREB-immunoreactive GVD-bearing neurons was varied among the cases, it was significantly greater in the hippocampus of AD compared with non-AD ($p = 0.00020$ by Mann-Whiteney's U test) (Fig. 6). pCREB-immunoreactive GVD-bearing neurons were occasionally found in the CA4 and subicular regions of AD brains, but barely detectable in the corresponding regions of non-AD brains. In both AD and non-AD brains, substantial numbers of neuronal axons distributed in the white matter of the motor cortex expressed intense pCREB immunoreactivity (Fig. 5, panel e). In both AD and non-AD brains, a subpopulation of reactive astrocytes and almost all ependymal cells expressed strong pCREB immunoreactivity, but it was located predominantly in their nuclei (Fig. 5, panel f). In both AD and non-AD brains, most neurons except for hippocampal pyramidal neurons did not express discernible pCREB immunoreactivity in their cell bodies and nuclei. Neither oligodendrocytes nor microglia expressed pCREB immunoreactivity in any cases examined.

4. Discussion

Since microarray analysis usually produces a large amount of gene expression data at one time, it is often difficult to find out the meaningful relationship be-

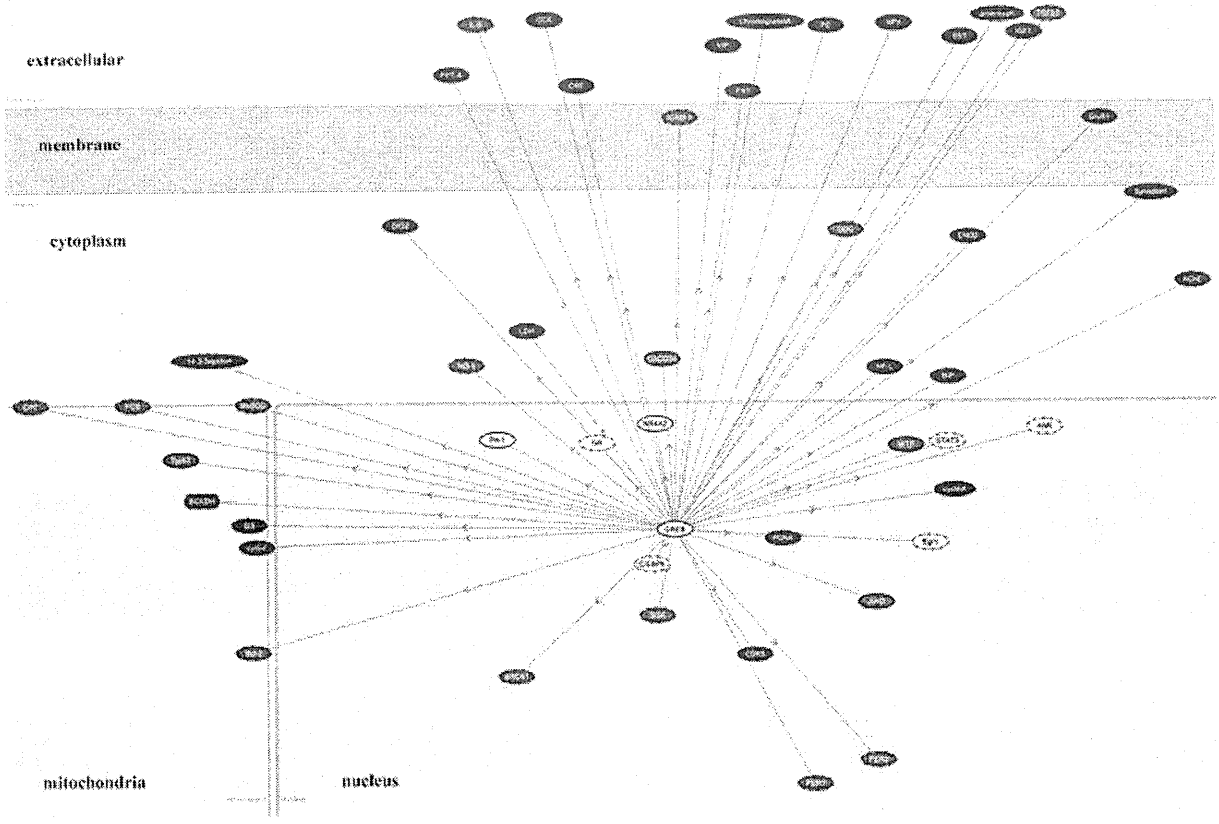

Fig. 2. The CREB-regulated transcriptional network of ADGs. The CREB-regulated transcriptional network extracted from the ADG network of Fig. 1 consists of a central node of CREB and 50 connecting nodes of CREB target genes listed in Table 1.

tween gene expression profile and biological implications from such a large quantity of available data. To overcome this difficulty, we have made a breakthrough to identify the molecular network most closely associated with microarray data by using a novel bioinformatics tool named KeyMolnet [12]. KeyMolnet includes the highly reliable information on a wide range of human proteins, small molecules, molecular relations, diseases, and drugs. All the contents are manually collected and carefully curated by experts from the literature and public databases. The application of KeyMolnet has an advantage that the user can easily merge microarray data with the comprehensive knowledgebase to characterize pathophysiologically meaningful networks from the high-throughput gene expression data [20,21]. In particular, the common upstream search is the most powerful approach to identify a battery of common transcription factors governing molecular networks closely associated with aberrant gene expression. By using KeyMolnet, we characterized the molecular network of 2,883 ADGs and 559 IADGs that show significant correlations with MMSE score and NFT burden in either all stages of AD or the early stage of AD [10]. We identified CREB as the central transcription factor that exhibits the most significant relevance to molecular networks of both ADGs and IADGs.

CREB is the prototype stimulus-inducible transcription factor binding as a dimer to a conserved cAMP-responsive element (CRE) of the target genes [18,19]. CREB is promptly activated in response to a wide range of extracellular stimuli, such as growth factors, peptide hormones, and neuronal activity, all of which activate various protein kinases such as PKA, mitogen-activated protein kinases (MAPKs), and Ca^{2+}/calmodulin-dependent protein kinases (CAMKs). They phosphorylate Ser-133 located in the KID domain of CREB. The phosphorylation of Ser-133 on CREB (pCREB) induces the recruitment of a transcriptional coactivator named CREB binding protein (CBP), thereby activates the expression of CRE-responsive genes. The CREB target genes play key roles in neuronal devel-

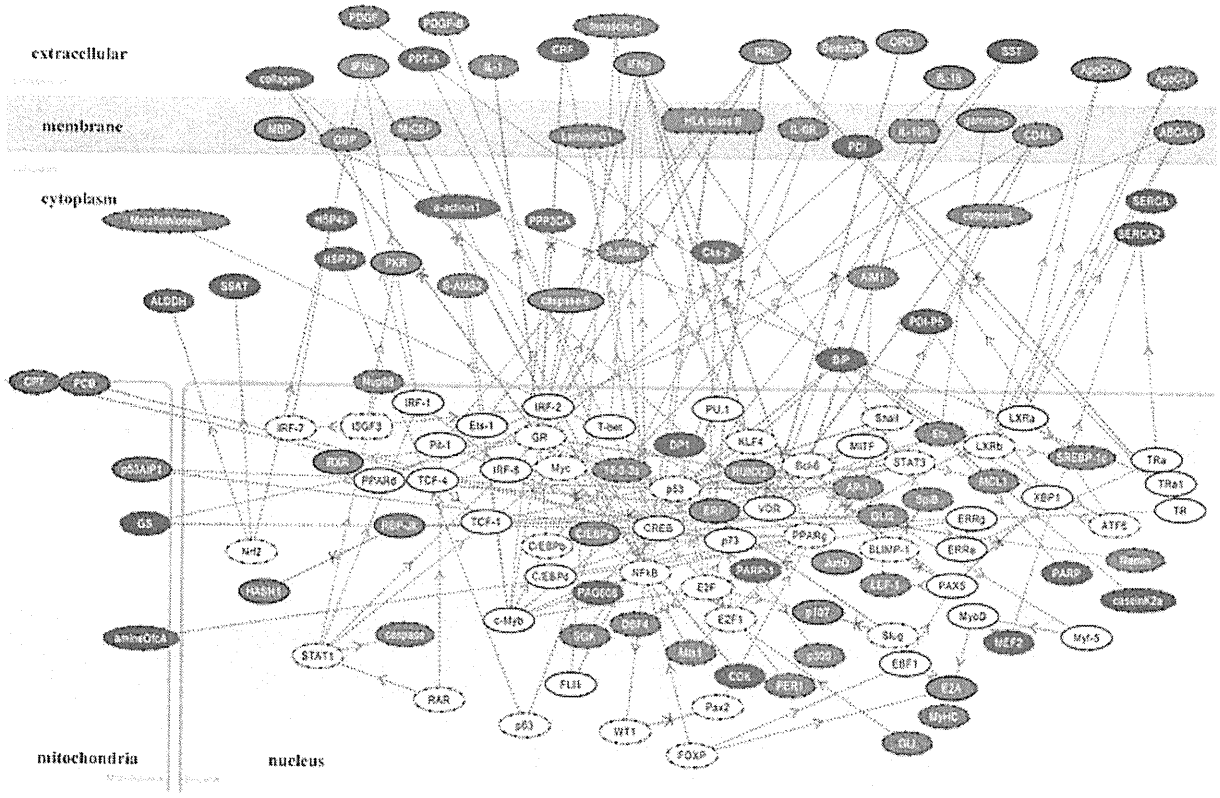

Fig. 3. Molecular network of incipient AD-related genes (IADGs). The list of 559 Entrez Gene IDs corresponding to IADGs was imported into KeyMolnet. The common upstream search of the core contents generated a network composed of 143 fundamental nodes with 190 molecular relations, arranged with respect to subcellular location of the molecules. Red nodes represent upregulated genes, whereas blue nodes represent downregulated genes. White nodes exhibit additional nodes extracted automatically from the core contents incorporated in the network to establish molecular connections. The direction of molecular relation is indicated by red-colored dash line with arrow (transcriptional activation) or blue-colored dash line with arrow and stop (transcriptional repression).

opment, synaptic plasticity, and neuroprotection in the central nervous system (CNS). Currently, we are able to search thousands of CREB target genes via the web-accessible database (natural.salk.edu/CREB) [22]. In the present study, the CREB-regulated transcriptional network consisted of both upregulated and downregulated sets of ADGs and IADGs. These observations suggest not simply either overactivation or hypoactivation of CREB but an involvement of generalized deregulation of the CREB signaling pathway in the pathophysiology of AD, emerging at the early stage of the disease.

To verify the *in silico* observations *in vivo*, we conducted immunohistochemical studies of 11 AD and 13 age-matched non-AD control brains by using anti-pCREB antibody. We identified aberrant pCREB immunoreactivity concentrated in granules of GVD in the hippocampus of both AD and non-AD brains, where the number of pCREB-immunoreactive GVD-bearing neurons was significantly greater in AD than non-AD cases. These results suggest that pCREB-immunoreactive GVD does not itself serve as an AD-specific diagnostic marker. However, these observations would support the hypothesis that sequestration of pCREB in GVD granules might be in part attributable to disturbed CREB-regulated gene expression in AD hippocampus.

Physiologically, CREB plays a pivotal role in the long-term memory formation in CA1 hippocampal neurons [23]. A previous study by western blot analysis showed that pCREB levels are reduced in AD brain tissues, although the cellular and subcellular location of pCREB was not characterized [24]. In a rat model, cortical impact injury induces a cognitive impairment, associated with reduced expression of CREB and target genes in the ipsilateral hippocampus [25]. A phosphodiesterase-4 inhibitor rolipram, by activating the cAMP/PKA/CREB signaling pathway, ameliorates deficits in long-term potential and cognitive function

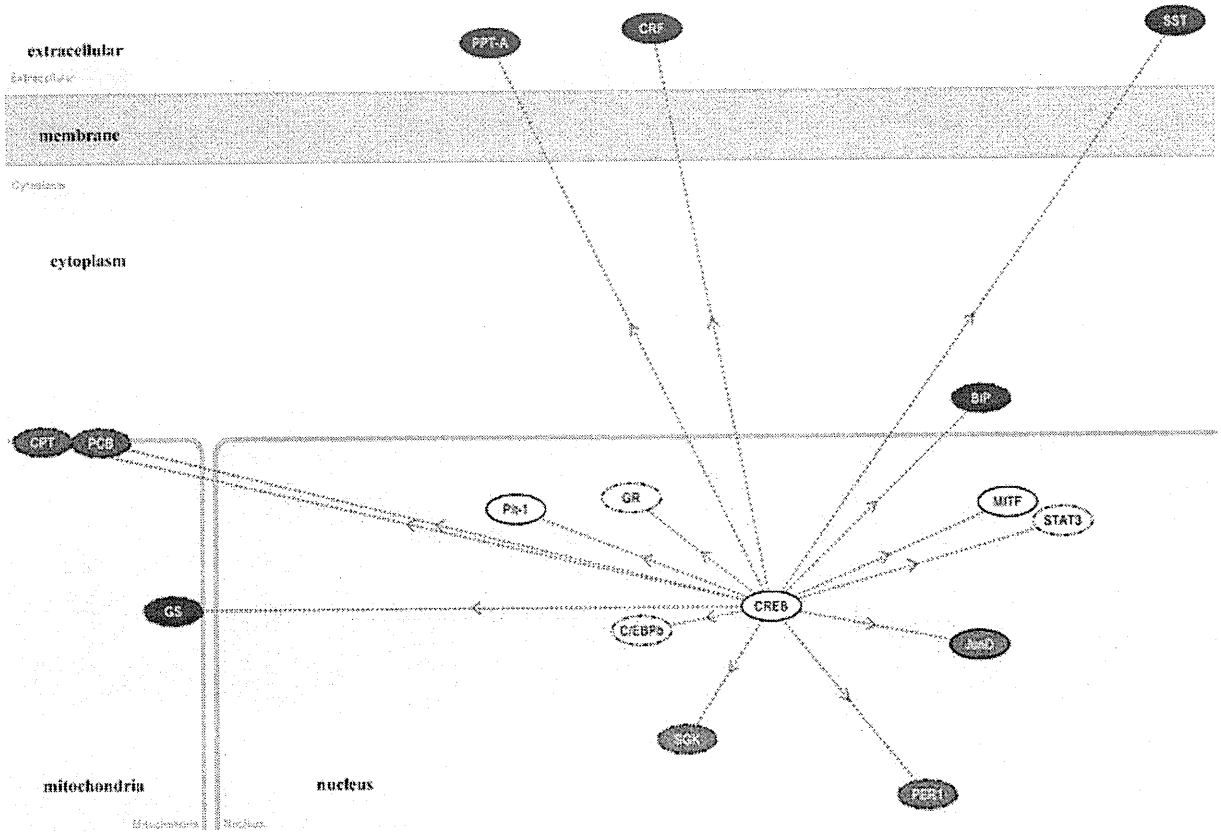

Fig. 4. The CREB-regulated transcriptional network of IADGs. The CREB-regulated transcriptional network extracted from the IADG network of Fig. 3 consists of a central node of CREB and 15 connecting nodes of CREB target genes listed in Table 1.

in a transgenic mouse model of AD [26]. Overactivation of calpain induces proteolysis of PKA subunits, resulting in inactivation of CREB in AD brains [27]. High levels of intracellular Aβ induce sustained hyperphosphorylation of CREB that blocks nuclear translocation of pCREB, resulting in inactivation of CREB-regulated gene expression [28]. The Aβ oligomers inactivate MAPKs, PKA, and cyclic GMP-dependent protein kinase essential for CREB activation in hippocampal neurons [29–31]. Long-term treatment with green tea catechin reduces the levels of Aβ oligomers, thereby restores the expression of CREB target genes, such as BDNF and PSD95, in the hippocampus [32]. All of these observations support a possible scenario that a defect in the CREB-mediated signaling pathway in hippocampal neurons causes cognitive disturbance during progression of AD. Therefore, CREB serves as a promising molecular target for treatment of dementia in AD [33].

The accumulation of misfolded cellular proteins within neurons, due to a defect in the clearance system, such as the ubiquitin-proteasome system (UPS) and the autophagic-lysosomal system, is a pathological hallmark of various neurodegenerative diseases [34]. Degradation of CREB involves nuclear export of CREB, modification by polyubiquitination, and processing for proteasomes, suggesting that UPS is a major system for CREB degradation under normal physiological conditions [35,36]. We identified an abnormal accumulation of pCREB in GVD granules of hippocampal neurons in AD brains. GVD is a pathological change characterized by electron-dense granules within double membrane-bound cytoplasmic vacuoles that highly resemble autophagosomes [37]. The emergence of GVD is confined to hippocampal pyramidal neurons of AD brains, and infrequently found in those of other neurodegenerative diseases. GVD is barely detectable in other brain regions. It plays a role in sequestration and degradation of unnecessary proteins and organelles in neurons exposed to aging-related stressful insults [37]. The active forms of caspase-3, glycogen synthase kinase-3β (GSK-3β), c-Jun N-terminal kinase

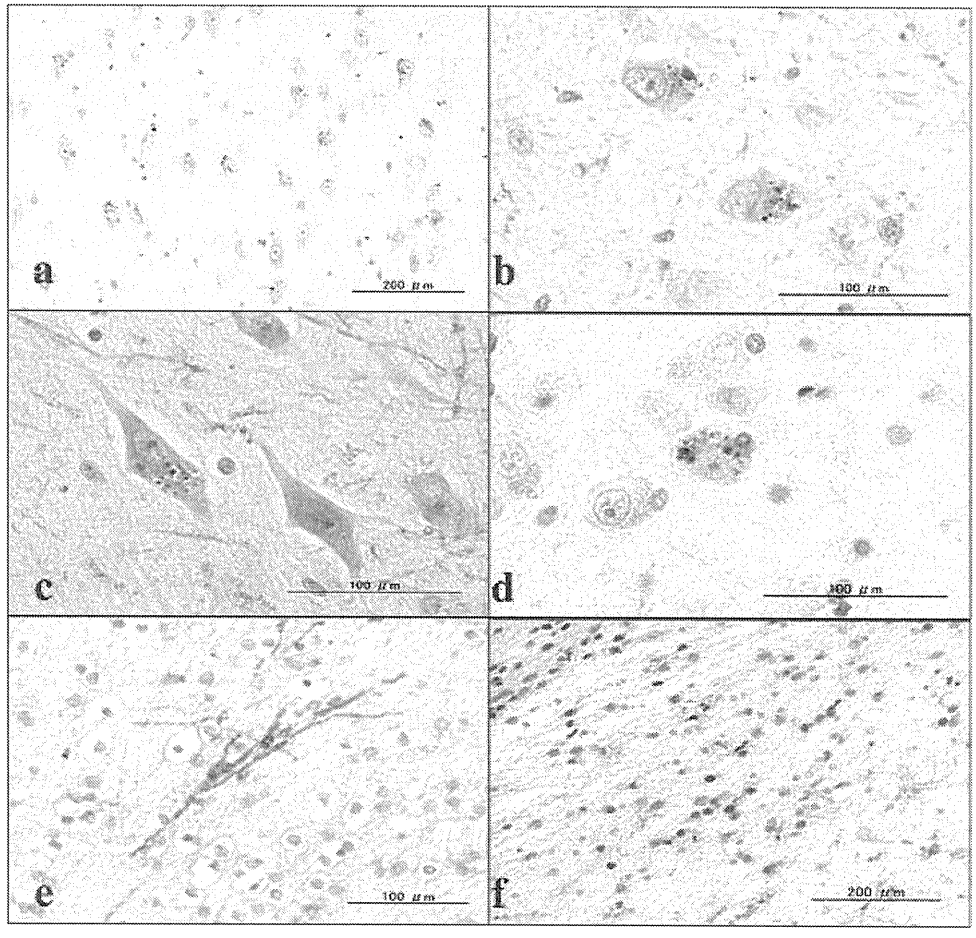

Fig. 5. pCREB immunoreactivity in AD and non-AD brains. The tissue sections of the hippocampus (HC) and the motor cortex (MC) of 11 AD patients and 13 other neurological disease (non-AD) patients were immunolabeled with an antibody against Ser-133-phosphorylated CREB (pCREB). (a) HC CA1 of a 59-year-old AD patient. The granular components of granulovacuolar degeneration (GVD) accumulated in the cytoplasm of pyramidal neurons exhibit strong pCREB immunoreactivity. (b) HC CA1 of a 68-year-old AD patient. The granular components of GVD accumulated in the cytoplasm of pyramidal neurons exhibit strong pCREB immunoreactivity. (c) HC CA3 of a 77 year-old AD patient. The vacuolar components of GVD are devoid of pCREB immunoreactivity. Neuritic processes of hippocampal neurons express variable levels of pCREB immunoreactivity. (d) HC CA1 of a 68 year-old myotonic dystrophy patient. The granular components of GVD accumulated in the cytoplasm of pyramidal neurons exhibit strong pCREB immunoreactivity. (e) MC of a 72-year-old AD patient. Substantial numbers of neuronal axons in the white matter of the motor cortex express strong pCREB immunoreactivity. (f) The periventricular white matter in the hippocampus of an 80 year-old AD patient. A subpopulation of reactive astrocytes express strong pCREB immunoreactivity located predominantly in their nuclei.

(JNK), c-Jun, pancreatic eIF2-alpha kinase (PERK), and TAR DNA-binding protein-43 (TDP-43), all of which are modified by phosphorylation, are found to be accumulated in GVD granules of hippocampal neurons in AD brains [38–43]. GVD granules also include cytoskeletal proteins, such as neurofilament, tubulin, and tau, along with ubiquitin [44,45]. At present, the precise implication of pCREB accumulation in GVD granules of hippocampal neurons in AD brains remains unknown. Importantly, degenerating neurons but not apparently healthy neurons in AD brains exhibit the profuse accumulation of autophagic vacuoles (AVs), owing to decreased clearance of AVs [46], suggesting an involvement of impaired autophagy function in formation of pCREB-accumulated GVD granules.

We found that neuronal axons, neuritic processes, and a subpopulation of reactive astrocytes also express pCREB immunoreactivity in both AD and non-AD brains. In a rat model of neuronal injury, reactive astrocytes express pCREB following intracerebroventricular injection of kinate [47]. In developing mouse DRG neurons, CREB protein is translated in response to NGF from the corresponding mRNA located in axons, and subsequently translocated to the cell body via a retro-

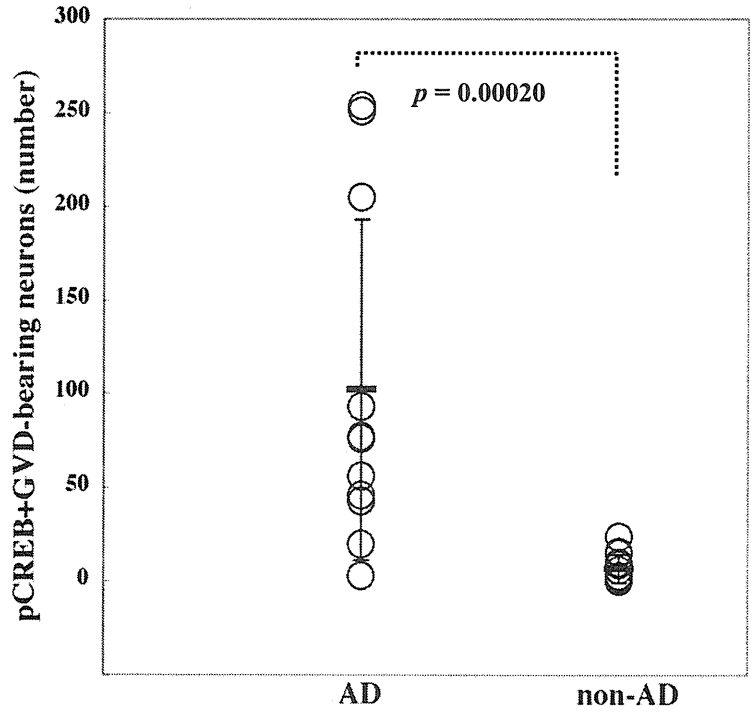

Fig. 6. The number of pCREB-immunoreactive GVD-bearing neurons in the hippocampus of AD and non-AD brains. The number of pCREB-immunoreactive GVD-bearing neurons was counted in the CA1, CA2, CA3 and CA4 sectors and the subiculum of the hippocampus, derived from 11 AD cases and 13 age and sex-matched other neurological disease (non-AD) cases. Non-AD cases include three patients with Parkinson disease (PD), two with multiple system atrophy (MSA), four with amyotrophic lateral sclerosis (ALS), and four with myotonic dystrophy. The total number in each case is plotted. The statistical difference in the numbers between AD and non-AD was evaluated by Mann-Whitney's U test.

grade axonal transport [48]. These observations would provide an explanation for glial or axonal location of CREB and pCREB.

We identified NF-κB-regulated gene expression as the second significant pathway in the molecular network of AGDs and IADGs (Supplementary Fig. 1 online). The NF-κB family, consisting of NF-κB1 (p50/p105), NF-κB2 (p52/p100), RelA (p65), RelB, and c-Rel, acts as a central regulator of innate and adaptive immune responses, cell proliferation, and apoptosis [49]. Under unstimulated conditions, NF-κB is sequestrated in the cytoplasm via non-covalent interaction with the inhibitor of NF-κB (IκB). Proinflammatory cytokines and stress-inducing agents activate specific IκB kinases that phosphorylate IκB proteins. Phosphorylated IκBs are ubiquitinated, and then processed for proteasome-mediated degradation, resulting in nuclear translocation of NF-κB that regulates the expression of hundreds of target genes by binding to the consensus sequence located in the promoter. Importantly, the expression of NF-κB p65 is enhanced in neurons, NFTs, and dystrophic neurites in the hippocampus and entorhinal cortex of AD brains [50]. A NF-κB-inducible microRNA, MiR-146a, reduces the expression of complement factor H (CFH), a negative regulator of proinflammatory responses in AD brains [51].

We also identified gene expression regulated by vitamin D receptor (VDR) as the third significant pathway in the molecular network of AGDs (Supplementary Fig. 2 online). Vitamin D plays a neuroprotective role by modulating neuronal calcium homeostasis. By forming a heterodimer with the retinoid X receptor (RXR), VDR activates the transcription of target genes with the vitamin D response element (VDRE) in the promoter. A significant association is found between VDR gene polymorphism and development of AD [52]. In AD brains, the expression of VDR and its target calbindin D28K is downregulated in hippocampal CA1 neurons [53].

In conclusion, KeyMolnet has effectively characterized molecular network of 2,883 ADGs and 559 IADGs. The common upstream search identified CREB as the principal transcription factor that regulates molecular networks of both ADGs and IADGs. Im-

munohistochemical study showed an abnormal accumulation of pCREB in GVD granules in hippocampal neurons of AD brains. These observations suggest that aberrant CREB-mediated gene regulation serves as a molecular biomarker of AD-related pathological processes, and support the hypothesis that sequestration of pCREB in GVD granules is in part responsible for deregulation of CREB-mediated gene expression in AD hippocampus.

5. Supplemental Material

Supplemental figures and tables can be found on http://www.my-pharm.ac.jp/~satoj/sub19.html as downloadable PDF files.

Acknowledegements

Human brain tissues were provided by Research Resource Network (RRN), Japan. This work was supported by a research grant to J-IS from the High-Tech Research Center Project, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan (S0801043), and from Research on Intractable Diseases, the Ministry of Health, Labour and Welfare of Japan.

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5 ゲノムワイド解析により同定された多発性硬化症のリスクアレル

Risk Alleles for Multiple Sclerosis Identified by a Genomewide Study

多発性硬化症(MS)では臨床的に明らかな遺伝的要因の関与を認める。本研究ではDNAマイクロアレイによるゲノムワイド関連(GWA)解析で、MSリスクアレルを同定した。931家系トリオのSNPをスクリーニングし、別の609家系トリオ、2,322孤発例MS、789コントロールと2種類の外部データベースコントロールで再現性を検証した。全12,360データを統合し、MSリスクの統計学的有意性を算出した。その結果、931家系トリオの334,923 SNPsにおけるTDTで、49 SNPsとMSの連関が示唆され、38 SNPsで検証した。931家系トリオ患者と2,431健常者間で差異を呈する32 SNPsを同定、110 SNPsで検証した。最終的に、IL-2受容体α鎖遺伝子(IL2RA)($p=2.96\times10^{-8}$)、IL-7受容体α鎖遺伝子(IL7RA)($p=2.94\times10^{-7}$)、HLA-DRA遺伝子座($p=8.94\times10^{-81}$)のSNPのアレルがMSと強く連関し、MSリスク遺伝因子と考えられた。

GWA解析の対象

MSは若年成人では最も多い中枢神経系炎症性自己免疫疾患である。MS双生児・兄弟例の解析から、何らかの遺伝因子がMS疾患感受性に影響していることが分かった。候補遺伝子解析で、主要適合性複合体(MHC)遺伝子座の多型とMSの関連が示唆された。730家系2,692サンプル4,506 SNPsの連鎖解析で、MHC遺伝子座との強い連鎖(LODスコア11.66)が証明された。しかし過去の研究では、統計学的検出力が不十分で、MSと連鎖するnon-MHC遺伝子を同定できなかった。

本研究では、バイアスや仮説の影響を受けないゲノムワイド関連(genome-wide association; GWA)解析により、MSリスクnon-MHC SNPアレルの同定を試みた。International MS Genetics Consortium (IMSGC)を立ち上げ、MS家系トリオと孤発例MSの血液サンプルはUK(全土)とUS(UCSF MS Center, San FranciscoとBWH MS Center, Bostonを中心)の研究グループが収集、ジェノタイピングにはAffymetrix社GeneChip Human Mapping 500K arrays (500,000 SNPs)を用いた。MSはMcDonald基準で診断したが、clinically isolated syndrome (CIS)(臨床的attack 1回)が4%(86症例)含まれている。コントロールサンプルは、BWH、UCSFで慢性炎症性疾患既往歴のない非ヒスパニック系白人より収集した。また外部データベースWellcome Trust Case Control Consortium (WTCCC), National Institute of Mental Health (NIMH)の双極性障害GWA研究のAffymetrix 400K SNPデータをコントロールとして取り込んだ。GWA解析は、I型・II型糖尿病、炎症性腸疾患、関節リウマチ、全身性エリテマトーデスのリスクnon-MHC SNPsの同定に成功している。

GWA解析のステージ化

本研究ではジェノタイピング効率化のため、解析をステージ化した。品質管理(QC)ステージでは、1,003家系トリオをタイピングし、ジェノタイピング率、Hardy-Weinberg平衡、Mendelianエラーの基準を満たすヨーロッパ系家系のサンプルを選択、対象を931家系トリオの334,923 SNPsに絞り込んだ。スクリーニングステージでは、931家系トリオの患者と両親を伝達不平衡テスト(TDT)で比較し、MSに連関する78 SNPs($p<1\times10^{-4}$)を同定した。931家系トリオの患者と2,431コントロール(WTCCC 1,475, NIHM 956)をCochran-Mantel-Haenszelテストで解析し、MSに連関する63 SNPs($p<0.001$)を同定した。自己免疫疾患感受性遺伝子座近傍の24 SNPs($p<0.01$)を追加解析した。再現性検証ステージでは、QC基準を満たす110 SNPsに関して、スクリーニングとは別の609家系トリオ、2,322孤発例MS(UK 928, US 1,394), 2,987コントロール(IMSGC 789, WTCCC 1,475, NIHM 723)を追加、Sequenom社iPLEX Gold MassArrayを用いて解析した。最後に全ステージ12,360サンプル(1,540家系トリオ、2,322孤発例MS、5,418コントロール)のデータを統合、UNPHASEDソフトで解析した。

MSリスクに関連するnon-MHC SNPsの意義

MHC遺伝子座HLA-DRB1*1501のSNP rs3135388 Aアレル($p=8.94\times10^{-81}$)が最も有意にMSリスクに関連していたが、他に比較的有意と判断された16 non-MHC SNPs: IL2RA (CD25)第1イントロンrs12722489 Cアレル($p=2.96\times10^{-8}$)とrs2104286 Tアレル($p=2.16\times10^{-7}$)、IL7RA (CD127)第6エクソンのアミノ酸置換(T244I)を伴うrs6897932 Cアレル

The International Multiple Sclerosis Genetics Consortium: *N Engl J Med* 357 (9): 851-862, 2007

($p=2.94\times10^{-7}$)、KIAA0350 (CLEC16A) rs6498169 Gアレル($p=3.83\times10^{-6}$)、CD58 rs12044852 Cアレル($p=1.90\times10^{-5}$)などを検出した(表)。IL2RAはI型糖尿病やバセドウ病との連関が報告されている。種々の自己免疫疾患でCD4$^+$CD25^{high}制御性T細胞の機能不全を認める。抗IL2RA抗体(rituximab)はMSで臨床試験中である。3つの候補遺伝子解析研究でも、IL7RAとMSの連関が報告されている。IL-7はメモリーT細胞プールの維持やγδT細胞の分化に重要なサイトカインである。IL7RA T244Iバリアントは可溶型と膜型受容体の構成比に関与し、I型糖尿病発症との連関が報告されている。本研究では、初めてnon-MHC SNPsとMSリスクとの連関を証明できた点に意義がある。

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表◉GWA解析で同定したMSリスクSNPとアレル

No.	染色体	遺伝子	一塩基多型(SNP)	リスクアレル	リスクアレル頻度	スクリーニング試験 931家系トリオの患者と両親の比較 p値	スクリーニング試験 931家系トリオ患者と2,431コントロールの比較 オッズ比(95%信頼区間)	スクリーニング試験 931家系トリオ患者と2,431コントロールの比較 p値	確認試験 2,522患者-600家系トリオと2,987コントロールの比較 オッズ比(95%信頼区間)	確認試験 2,522患者-600家系トリオと2,987コントロールの比較 p値	統合データ 全サンプル p値	統合データ 全サンプル オッズ比(95%信頼区間)	アレル層別解析 DRB1*1501陽性群(n=931) p値	アレル層別解析 DRB1*1501陰性群(n=400) p値
1	6q21	HLA-DRA	rs3135388	A	0.23						8.94×10^{-61}	1.99 (1.84-2.15)		
2	10p15	IL2RA	rs12722489	C	0.85	1.28×10^{-3}	1.35 (1.13-1.62)	9.61×10^{-4}	1.20 (1.11-1.52)	4.56×10^{-4}	1.10 (1.00-1.31)	2.96×10^{-3}	1.25 (1.16-1.36)	8.59×10^{-7}	6.19×10^{-3}
3	10p15	IL2RA	rs2104286	T	0.75	3.25×10^{-3}	1.26 (1.08-1.47)	2.85×10^{-3}	1.26 (1.11-1.43)	1.49×10^{-4}	1.16 (1.08-1.25)	2.16×10^{-5}	1.19 (1.11-1.26)	3.19×10^{-7}	4.44×10^{-3}
4	5q13	IL7RA	rs6897932	C	0.75	5.78×10^{-3}	1.24 (1.07-1.44)	1.65×10^{-3}	1.17 (1.03-1.32)	0.75×10^{-2}	1.10 (1.03-1.17)	2.94×10^{-3}	1.18 (1.11-1.25)	1.17×10^{-7}	1.58×10^{-3}
5	12q13	CLEC16A	rs6498169	G	0.37	2.90×10^{-3}	1.16 (1.02-1.33)	6.51×10^{-3}	1.17 (1.04-1.31)	1.69×10^{-2}	1.16 (1.09-1.24)	3.82×10^{-6}	1.14 (1.08-1.21)	9.50×10^{-7}	1.60×10^{-1}
6	1p22	RPL5	rs6604025	C	0.23	4.45×10^{-4}	1.29 (1.11-1.50)	2.34×10^{-3}	1.25 (1.11-1.40)	9.58×10^{-6}	1.13 (1.05-1.22)	7.04×10^{-5}	1.15 (1.08-1.22)	2.06×10^{-7}	7.42×10^{-1}
7	9q33	DBC1	rs10984447	A	0.77	1.18×10^{-3}	1.36 (1.16-1.59)	2.13×10^{-4}	1.09 (0.95-1.24)	1.27×10^{-2}	1.14 (1.05-1.24)	8.46×10^{-6}	1.17 (1.09-1.25)	2.07×10^{-7}	1.23×10^{-1}
8	1q13	CD58	rs12044852	C	0.92	9.71×10^{-4}	1.40 (1.17-1.67)	3.01×10^{-4}	1.54 (1.26-1.89)	2.06×10^{-5}	1.20 (1.07-1.35)	1.90×10^{-5}	1.24 (1.12-1.37)	4.52×10^{-8}	3.57×10^{-1}
9	2p23	ALK	rs7577363	A	0.03	1.14×10^{-4}	2.14 (1.43-3.20)	1.21×10^{-4}	1.44 (0.98-1.92)	3.15×10^{-4}	1.54 (1.11-1.62)	7.37×10^{-5}	1.37 (1.17-1.61)	9.22×10^{-6}	1.38×10^{-1}
10	1p22	FAM69A	rs7536563	A	0.38	2.53×10^{-3}	1.34 (1.16-1.55)	2.48×10^{-4}	1.14 (1.02-1.27)	2.17×10^{-2}	1.08 (1.01-1.16)	9.12×10^{-5}	1.12 (1.06-1.18)	5.09×10^{-7}	1.39×10^{-1}
11	1p22	FAM69A	rs11164838	C	0.57	6.91×10^{-3}	1.32 (1.15-1.52)	3.28×10^{-4}	1.18 (1.06-1.32)	1.20×10^{-2}	1.09 (1.02-1.16)	1.91×10^{-2}	1.11 (1.05-1.18)	3.56×10^{-7}	4.23×10^{-2}
12	9q24	ANKRD15	rs10975200	G	0.18	8.05×10^{-3}	1.25 (1.06-1.50)	9.95×10^{-3}	1.37 (1.16-1.59)	2.12×10^{-4}	1.11 (1.02-1.21)	3.23×10^{-2}	1.14 (1.06-1.23)	1.62×10^{-7}	1.62×10^{-2}
13	1p22	EVI5	rs10735781	G	0.38	2.21×10^{-3}	1.29 (1.12-1.50)	6.05×10^{-4}	1.17 (1.05-1.30)	2.01×10^{-3}	1.08 (1.01-1.16)	3.25×10^{-2}	1.11 (1.05-1.18)	1.93×10^{-7}	3.33×10^{-1}
14	1p22	EVI5	rs6689578	T	0.38	3.45×10^{-3}	1.29 (1.11-1.49)	8.98×10^{-4}	1.17 (1.05-1.31)	1.56×10^{-3}	1.09 (1.01-1.16)	5.00×10^{-3}	1.11 (1.04-1.17)	2.19×10^{-7}	4.21×10^{-2}
15	12p13	KLRB1	rs4763055	A	0.38	4.55×10^{-3}	1.15 (1.00-1.32)	2.16×10^{-2}	1.19 (1.07-1.33)	1.43×10^{-3}	1.09 (1.01-1.16)	6.85×10^{-3}	1.10 (1.04-1.17)	2.61×10^{-7}	7.65×10^{-2}
16	3q13	CBLB	rs12497066	T	0.73	7.65×10^{-3}	1.22 (1.05-1.41)	8.09×10^{-3}	1.29 (1.14-1.46)	3.53×10^{-5}	1.09 (1.00-1.16)	5.43×10^{-3}	1.09 (1.03-1.16)	1.14×10^{-7}	2.32×10^{-2}
17	1q31	PDE4B	rs1327172	C	0.49	8.77×10^{-3}	1.12 (0.95-1.27)	9.57×10^{-3}	1.15 (1.04-1.28)	3.95×10^{-3}	1.07 (1.01-1.14)	6.06×10^{-3}	1.08 (1.02-1.14)	2.36×10^{-7}	2.16×10^{-1}

Remark

日本人MSには適応が難しい

佐藤 準一

多因子疾患は、複数の遺伝子変異と環境因子の相互作用により発症が規定される。個々の疾患関連遺伝子多型(SNP)は単独では浸透率が低く、発症を誘導しない。しかしこのようなSNPsと環境因子が複数共存すると、疾患としての表現型(phenotype)が誘導される。従来の研究では、罹患者を2人以上有する家系(罹患同胞対など)を多数収集し、マイクロサテライトマーカー(全ゲノムで数万個)を指標に候補遺伝子座(ロッドスコア>3.0)を同定する連鎖解析(linkage analysis)が主流であったが、多数の家系が必要で検出感度が低かった。SNP(対立遺伝子の頻度の低いアレルの頻度が1%以上)はゲノム上に高密度に存在(全ゲノムで数百万個)し、マイクロアレイが普及してハイスループットスクリーニングが可能となり、ゲノムワイドの関連解析が容易となった。本研究ではヨーロッパ系非ヒスパニック白人MSと健常者の膨大なサンプルで統計学的検出力を高めてGWA解析を行い、IL2RA, IL7RAのSNPとMSの連関を見いだした。しかし同定された個々のnon-MHC SNPsはp値が高く、関与は軽微と判断された。

MSは再発を反復し、多巣性病巣を認める中枢神経系炎症性脱髄疾患と定義されるが、不均一な病因に起因する疾患群と考えられる。本研究ではRRMS, SPMS, PPMS, CIS(MRIで視神経・脊髄・脳幹・小脳に2病巣以上)を一括してMSとしたが、これらが同一のgenetic backgroundを有するというエビデンスはない。また抗AQP4抗体を測定していないため、neuromyelitis optica(NMO)混入の可能性を否定できない。したがってサブグループ別のGWA解析が必要となる。またSNPアレル頻度の人種差(ethnic differences)を考慮すると、本研究の結果は日本人MSには適応困難と思われる。

Lecture

解　説

多発性硬化症の病態形成とオーファン核内受容体NR4A2*

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Key Words: multiple sclerosis, NR4A2, nuclear receptor, IL-17, Th17 cell, transcription factor, autoimmune disease

はじめに

多発性硬化症(multiple sclerosis；MS)は，Th1細胞やTh17細胞をはじめとする炎症性エフェクターT細胞の機能亢進が病態形成に深くかかわる典型的な自己免疫疾患の一種である[1)2)]．われわれは，MSの新規治療法の可能性を探るため，DNAマイクロアレイによるMS患者末梢血T細胞の網羅的遺伝子発現解析を行い，健常者に比較してMS患者T細胞で発現が変動する遺伝子群の同定を試みた[3)]．その後，MS患者でもっとも有意な発現亢進を認めた遺伝子の一つとして同定したオーファン核内受容体NR4A2に着目した．TリンパにおけるNR4A2の高発現は，MSの動物モデルである実験的自己免疫性脳脊髄炎(experimental autoimmune encephalomyelitis；EAE)マウスの中枢神経浸潤T細胞でも認められ，炎症性サイトカイン産生と相関したことから，病態形成との関連についてさらに解析をすすめた．遺伝子導入によるT細胞のNR4A2発現の増加や，NR4A2特異的siRNA処理によるNR4A2発現の抑制が，IL-17やIFN-γなどの炎症性サイトカインの産生と連動したことから，NR4A2がこれらの炎症性サイトカイン産生制御に関与することが明らかとなった．さらに，このNR4A2特異的siRNAは，脳炎惹起性T細胞を移入することによりレシピエントに発症を誘導するpassive EAEモデルにおいて，移入T細胞を前処理することでEAEの発症を有意に抑制したことから，NR4A2が，病原性T細胞の炎症性サイトカイン産生制御を作用点として，MSなどの自己免疫疾患の新規治療ターゲットになりうる可能性が示された[4)]．本稿では，MS/EAEの病態形成におけるNR4A2の挙動と，炎症性サイトカイン産生制御を介したMSの新規治療法の可能性について紹介する．

オーファン核内受容体NR4A2とは？

NR4A2は，エストロゲン受容体やレチノイン酸受容体などを含む核内受容体ファミリーの一員であり，ヒトの場合48種類の異なる分子が同定されている．NR4A亜群の分子はNR4A1，NR4A2，NR4A3の3種からなるが，他の核内受容体と同様，NGFB-I/Nur77(＝NR4A1)やNurr1(＝NR4A2)などの別名もいまだに汎用されている[5)]．NR4Aファミリー分子は図1に示すようなさまざまな生体応答にかかわることが知られており，その一部には分子間の機能的オーバーラップが認められる．NR4A2の主な発現部位は比較的中枢神経系(CNS)に集中しており，なかでも中脳腹側，脳幹や脊髄に強い発現を認めるが，実は免疫系でもT細胞受容体の架橋や炎症性サイトカインなどの刺激により，T細胞で一過性に発現誘導されるimmediate early geneとして知られている．NR4Aファミリー分子を含む核内受容体分子は，複数の機能ドメインからなる構造が比較的保存されている(図1)．2つのZnフィ

* Possible involvement of orphan nuclear receptor NR4A2 in pathogenesis of multiple sclerosis.

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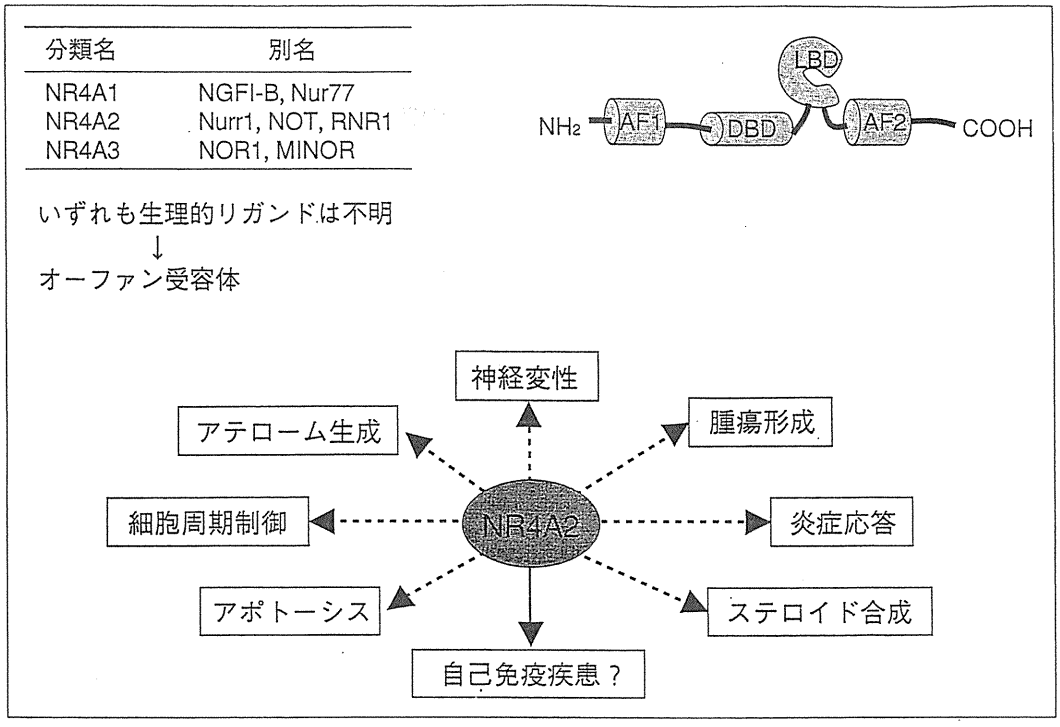

図1　NR4A核内受容体ファミリー分子

哺乳動物のNR4A核内受容体ファミリー分子は，NR4A1(NFGI-B/Nur77)，NR4A2(Nurr1)，NR4A3(NOR1)の3種の分子からなり，ファミリー分子に共通の構造(AF1/2, DBD, LBD)を有する核内受容体分子である．いずれも生理的なリガンドは不明であるが，図に示すようなさまざまな生体応答にかかわることが知られている．免疫系との関連では，遺伝子欠損マウスを用いた解析から，NR4A1とNR4A3が胸腺細胞のアポトーシスにかかわることが示されており，いわゆる「負の選択」の過程で重要な役割を果たしているものと考えられる．一方，NR4A2欠損マウスではDA産生ニューロンの分化が著しく阻害されるが，胸腺細胞分化は比較的正常に保たれることが示されており，NR4A1/NR4A3とNR4A2の機能的な相違をうかがわせる知見である．AF1, 2：activation function 1, 2, DBD：DNA結合領域，LBD：リガンド結合領域

ンガーからなるN末側のDNA結合ドメイン(DBD)は，受容体間で非常によく保存されており，標的分子プロモーター内の応答配列に対する特異的結合にかかわる．C末側に位置するリガンド結合ドメイン(LBD)は，各核内受容体分子間での多様性が高く，それぞれ異なるリガンドを認識する．一般に核内受容体は，リガンドの結合により受容体のコンフォメーションが変化し，コリプレッサーを遊離してコアクチベーターと会合することで転写活性化能を獲得する．一方，リガンドが未知の核内受容体はオーファン受容体と呼ばれ，NR4Aファミリー分子もこの中に含まれる．LBDの構造解析の結果，NR4A2のLBDはかさ高い芳香環や疎水性の側鎖をもつアミノ酸に覆われており，典型的なリガンド結合ポケットがないことが示された[6]．そしてNR4A2は，リガンドの存在とは無関係に活性型受容体類似のコンフォメーションをとることが示され，リガンド非依存的に転写活性化能を有するものと考えられている．

NR4A2の誘導因子とターゲット分子[5]

NR4A2は，脂肪酸，プロスタグランジン，カルシウム，増殖因子，ペプチドホルモン，神経伝達分子などの因子に応答するのみならず，ストレスや物理刺激などにも反応してすみやかに発現が誘導される．これらの刺激はいずれもNF-κBあるいはCREBの活性化を誘導し，NR4A2遺伝子プロモーターの転写活性化領域に結合することで，遺伝子発現をひき起こすと考えられている．一方，発現したNR4A2分子は，特定のDNA配列を認識して下流の遺伝子発現を誘導する(図2)．これまでにNR4Aファミリー分子が認識するDNA配列として，①(A/T)AAAGGTCA配列からなる