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Short Report

An 8-week, open-label, dose-finding study of nimodipine for the treatment of progranulin insufficiency from *GRN* gene mutations

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Abstract

Introduction: Frontotemporal lobar degeneration–causing mutations in the progranulin (*GRN*) gene reduce progranulin protein (PGRN) levels, suggesting that restoring PGRN in mutation carriers may be therapeutic. Nimodipine, a Food and Drug Administration–approved blood-brain barrier-penetrant calcium channel blocker, increased PGRN levels in PGRN-deficient murine models. We sought to assess safety and tolerability of oral nimodipine in human *GRN* mutation carriers.

Methods: We performed an open-label, 8-week, dose-finding, phase 1 clinical trial in eight *GRN* mutation carriers to assess the safety and tolerability of nimodipine and assayed fluid and radiologic markers to investigate therapeutic endpoints.

Results: There were no serious adverse events; however, PGRN concentrations (cerebrospinal fluid and plasma) did not change significantly following treatment (percent changes of $-5.2 \pm 10.9\%$ in plasma and $-10.2 \pm 7.8\%$ in cerebrospinal fluid). Measurable atrophy within the left middle frontal gyrus was observed over an 8-week period.

Discussion: While well tolerated, nimodipine treatment did not alter PGRN concentrations or secondary outcomes.

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1. Introduction

Mutations in the progranulin gene (*GRN*) are a common cause of inherited frontotemporal dementia (FTD). *GRN* mutations cause haploinsufficiency, with only one functional copy of the gene remaining. Progranulin protein (PGRN) levels are less than 50% from birth [1–3]. Thus, therapeutic approaches have focused on increasing PGRN levels, either by increasing transcription from the normal allele [4,5] or by modulating posttranslational mechanisms [6,7].

Promising preclinical data in heterozygous *Grn* mice suggested that nimodipine might restore PGRN levels in humans with *GRN* mutations. As PGRN levels are stable over both short and long periods (1 week to 2 years) in *GRN* mutation carriers [8] as well as various disease and control populations [9], PGRN levels alone are suitable endpoints for trials. We tested the effects of modulators of calcium homeostasis on PGRN levels in cultured cells and found that reducing intracellular calcium by blocking calcium channels increased PGRN secretion. We focused on nimodipine, a Food and Drug Administration–approved L-type calcium channel blocker that crosses the blood-brain barrier, as it is relatively well tolerated and, in a placebo-controlled trial, it improved overall status and cognitive function in patients with dementia [10].

We report the effects of nimodipine on PGRN levels in plasma and central nervous system tissues in correlative studies on animals and humans carrying *GRN* mutations. In a phase 1, 8-week open-label clinical trial, we sought to determine the safety and tolerability of oral nimodipine treatment in *GRN* mutation carriers and the best dose of nimodipine for long-term efficacy studies. As secondary objectives, we investigated the effects of nimodipine on PGRN levels in plasma and cerebrospinal fluid (CSF), a subset of inflammatory and neurodegeneration-associated proteins, and in brain volumes.

2. Methods

2.1. Study oversight

This study was approved under local institutional review board's supervision, registered at ClinicalTrials.gov (NCT01835665). Informed consent was obtained from patients and, when applicable, caregivers.

2.2. Study design and enrollment

The target enrollment was eight asymptomatic and/or symptomatic carriers of known FTD-causing *GRN* mutations (Supplementary Fig. 2). Participants were required to be aware of their mutation status before screening. Participants were enrolled from March 2013 until January 2015. Inclusion and exclusion criteria are listed in Supplementary Materials.

Because nimodipine is a Food and Drug Administration–approved drug at a dose of 360 mg per day, we chose a titration to 360 mg or maximum tolerated dose. Nimodipine was titrated every week as follows: 30 mg orally TID, 60 mg TID, 90 mg TID, and 90 mg QID and maintained at this dose for 4 weeks. All subjects attempted to titrate to the full 360 mg per day dose (Supplementary Fig. 3).

2.3. Outcomes

Primary outcomes were safety and tolerability of nimodipine and identification of the optimal nimodipine dose for long-term efficacy studies in *GRN* mutation carriers. Safety was measured by the number of treatment emergent adverse events (listed by detailed MedDRA term [www.meddra.org]), routine clinical, laboratory, and electrocardiogram assessments. Secondary outcomes were change from baseline concentration of plasma PGRN or CSF PGRN, plasma PGRN-related inflammatory markers (c-reactive protein [CRP], erythrocyte sedimentation rate [ESR]), CSF neurodegeneration proteins (neurofilament light chain [NfL], amyloid β 42 [$A\beta_{42}$], tau), blood and CSF cytokines (interleukin-10 [IL-10], IL-2, IL-6, IL-8, and tumor necrosis factor α [TNFα]), and volumetric magnetic resonance imaging (MRI).

2.4. Plasma and CSF sampling and analysis

PGRN was measured by A&G Pharma (Columbia, MD) using a proprietary enzyme-linked immunosorbent assay that detects full-length PGRN. TNFα was measured by Quanterix (Lexington, MA). Tau, phospho-tau_{181}, and $A\beta_{42}$ levels were analyzed using the xMAP multiplex immunoassay/Luminex analyzer (INNO-BIA AlzBio3; Fujirebio). NfL levels were measured using the UmanDiagnostics kit (Umeå, Sweden). Proinflammatory cytokines were measured in plasma and CSF using a V-PLEX human proinflammatory 10-Plex kit from Meso Scale Discovery (Rockville, MD). Nonparametric measures (Mann-Whitney U) were used to compare mean baseline versus 8-week or early termination values of the secondary clinical and laboratory measures.

2.5. Brain imaging

MRI was performed at screening and completion of the study using a 3T Siemens scanner [11]. MP-RAGE scans for both time points for a given subject were registered to

Table 1
Characteristics of study participants

Clinical	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Mean
Clinical phenotype (clinicians' impression)	nfvPPA	Asymptomatic	Asymptomatic	bvFTD	bvFTD	Asymptomatic	bvFTD	Asymptomatic	-
CDR-SB	0	0.5	0	12	4	0	2	0	2.3
MMSE	29	29	30	-	22	30	25	30	27.9
Completed 8 weeks?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	-
Max dose achieved (mg)	360	360	360	360	180–270	360	360	180	-
Plasma									Mean ± SEM
GRN ng/mL, (% change)	1.1 (21)	1.4 (19)	−12.6 (−53)	−0.2 (−2)	4.9 (23)	−1.5 (−16)	−3.4 (−27)	-	−1.47 ± 2.1 (−5.2 ± 10.9)
ESRmm/hour, (% change)	2 (40)	nd	0 (0)	0 (0)	19 (91)	24 (500)	−5 (−31)	-	6 ± 4.3 (99.9 ± 81.8)
CRP mg/L, (% change)	0.4 (14)	−0.1 (−1)	1.2 (92)	−1.7 (39)	6.8 (145)	5.9 (590)	0.1 (6)	-	1.8 ± 1.2 (115.4 ± 62.5)
CSF									
GRN ng/mL, (% change)	−0.07 (−13)	0.06 (27)	−0.15 (−18)	−0.2 (−27)	−0.28 (−41)	0.06 (15)	−0.05 (−12)	−0.08 (−17)	−0.09 ± 0.04 (−10.7 ± 7.8)
NfL pg/mL, (% change)	211.8 (5)	−39.5 (−12)	−7.4 (0)	750.6 (5)	−654.5 (−8)	71.4 (9)	−499.9 (−5)	−77.9 (−7)	−30.68 ± 151.8 (−1.4 ± 2.5)
$A\beta_{42}$ pg/mL, (% change)	−8.7 (−1)	−81.6 (−15)	76.8 (11)	19.7 (4)	−46.3 (−14)	−35.4 (−6)	−58.3 (−12)	−103.9 (−19)	−29.70 ± 20.5 (−6.5 ± 3.6)
Tau pg/mL, (% change)	4.2 (7)	−4.2 (−14)	−0.4 (−1)	25.8 (25)	10.0 (12)	−6.7 (−16)	2.2 (−3)	2.0 (5)	3.59 ± 3.7 (1.9 ± 4.8)
P-tau pg/mL, (% change)	−1.7 (−7)	5.8 (31)	−0.8 (−3)	−3.0 (−13)	2.0 (17)	−8.0 (−34)	7.8 (89)	1.6 (13)	0.48 ± 1.8 (11.6 ± 13.1)
IL-10 pg/mL, (% change)	0.03 (6)	0.001 (−1)	0.005 (−5)	0.01 (11)	−0.01 (−15)	-	0.003 (4)	0.04 (65)	0.00 ± 0.1 (9.1 ± 9.8)
IL-2 pg/mL, (% change)	0.01 (10)	0.01 (31)	0.03 (62)	−0.02 (−33)	0 (9)	-	0.03 (36)	0.01 (14)	0.01 ± 0.01 (18.5 ± 11.2)
IL-6 pg/mL, (% change)	0.11 (6)	−0.15 (−11)	−0.04 (−3)	0.07 (7)	0.14 (13)	-	0.11 (16)	0.06 (8)	0.04 ± 0.04 (5.1 ± 3.5)
IL-8 pg/mL, (% change)	3.82 (5)	1.24 (4)	−0.38 (−1)	6.74 (9)	4.65 (11)	-	−1.72 (−6)	−0.16 (0)	2.0 ± 1.17 (3.1 ± 2.2)
TNFα pg/mL, (% change)	0.00 (0)	−0.05 (−38)	0.02 (14)	−0.07 (−16)	0.04 (42)	-	0.00 (−1)	0.01 (9)	0.01 ± 0.02 (1.4 ± 9.4)

Abbreviations: $A\beta_{42,}$ amyloid β; CDR-SB, Clinical Dementia Rating–sum of boxes; CSF, cerebrospinal fluid; GRN, progranulin; CRP, c-reactive protein; ESR, erythrocyte sedimentation rate; MMSE, Mini–Mental State Examination; nd, not determined; NfL, neurofilament light chain; P-tau, phospho-tau; TNFα, tumor necrosis factor α.

NOTE. Age and gender were not shown to maintain participant confidentiality.

one another using the serial longitudinal anatomical MRI package in SPM12 [12], and the procedures outlined elsewhere [13].

3. Results

3.1. Preclinical studies

Cultured cellular models revealed that cytosolic calcium levels affected the secreted PGRN levels (Supplementary Fig. 1). Two-week treatment with nimodipine elevated hippocampal PGRN levels in both wild-type ($P < .001$) and $Grn^{+/-}$ mice ($P < .05$) compared to vehicle-treated mice (Supplementary Fig. 1).

3.2. Demographics

Eight *GRN* mutation carriers were enrolled in the trial (Table 1), with a median age of 57.3 years; 50% were male. They included three behavioral-variant FTD (bvFTD), one nonfluent-variant primary progressive aphasia (nfvPPA), and four asymptomatic individuals. One self-reported asymptomatic participant had a 0.5 in judgment on the Clinical Dementia Rating–sum of boxes (CDR-SB) and thus fit into the classification of normal with concerns.

3.3. Safety and tolerability

Two of the eight participants (25%) were unable to titrate to the maximum dose of 360 mg per day (Table 1). One participant discontinued treatment early at week 5 due to dizziness, palpitations, and malaise. Another discontinued due to edema. There were no serious adverse events. Forty-three adverse events were reported; the most common included edema (12 reports), headache (3), and dizziness (3). There were also two reports of arrhythmia and lassitude. There were single reports of upper respiratory infection, flu-like symptoms, syncope, redness on legs, depression, insomnia, worsening of asthma, and urinary tract infection.

3.4. Fluid biomarkers

PGRN concentrations, in plasma and CSF, did not change from baseline after nimodipine treatment (percent changes of $-5.2 \pm 10.9\%$ [mean $\pm$ standard error mean] in plasma and $-10.2 \pm 7.8\%$ in CSF) (Table 1 and Fig. 1A and 1B).

CSF levels of three neurodegenerative disease–associated proteins, NfL, $A\beta_{42}$, and tau (both total tau and phospho-tau) did not change significantly after nimodipine treatment (Table 1). Levels of CSF NfL ($P = .0002$, Mann-Whitney U) and tau ($P = .0002$, Mann-Whitney U) at baseline correlated with disease severity as measured by CDR-SB, with the highest levels of NfL and tau observed in subjects with the highest CDR-SB score (Fig. 1C and 1D).

Of 10 cytokines measured in CSF, five were detectable (IL-10, IL-2, IL-6, IL-8, and TNFα), and none exhibited a significant change following nimodipine treatment (Table 1).

3.5. Volumetric MRI

Longitudinal structural MRI differences were determined by performing a one-sample t-test on the longitudinal Jacobian gray matter change maps. Six subjects were analyzed (mean age = 56.2 years, range 32.5–69.0; 4 females; mean interscan interval = 50.7 days, range 29–70). The resultant map was corrected with a joint height/extent threshold of $P < .001$ (no significant reductions were detected at a more stringent threshold of $P < .05$, family-wise error corrected). There was one significant cluster of gray matter loss in the left middle frontal gyrus. The rate of change in this cluster revealed that the effect was driven by four subjects with annualized rates of gray matter loss between 1% and 2% (Fig. 1).

4. Discussion

PGRN deficiency causes FTD; therefore, treatments that restore PGRN levels are of high therapeutic interest. We found that oral nimodipine increased mouse hippocampal PGRN concentrations but failed to increase human PGRN levels in plasma and CSF. In an 8-week, open-label trial, nimodipine was safe and well tolerated in *GRN* mutation carriers, but no effects of nimodipine were noted on secondary outcome measures, including concentrations of PGRN in blood and CSF, CSF NfL, CSF $A\beta_{42}$, CSF total tau, CSF phospho-tau, plasma ESR, plasma CRP, or CSF cytokines (IL-10, IL-2, IL-6, IL-8, and TNFα). Although there were no clear effects on volumetric MRI measurements by nimodipine, there was volume loss noted in severely affected patients. Reasons for the discrepancy between rodents and humans are unknown and may be related to many factors, including exposure, dose, timing, and interspecies difference in responsiveness.

Of the six participants with MRIs conducted before and after treatment, three were asymptomatic and three were symptomatic. The most severely affected cases displayed the greatest decrease in volume over the trial period; a change that would extrapolate to a 1%–2% loss in the volume of the left frontal region annually, if constant. This rate is slightly less than reported for whole-brain atrophy in a comparably sized group of *GRN* mutation carriers assessed with MRI scans over 2 years [14]. Intermediate volume loss was observed in a mildly symptomatic individual and in an asymptomatic individual with a score of 0.5 on CDR-SB for judgment. The two asymptomatic cases revealed no change in brain volume. Given that nimodipine did not raise levels of PGRN, we propose this rate of decline may be comparable to untreated *GRN* mutation carriers. However, we cannot exclude a contribution of volume loss from treatment with nimodipine. If this rate of volume loss is confirmed in a larger cohort of mutation carriers, slowing or reversal of regional gray matter loss could be a viable endpoint in future FTD-GRN clinical trials.

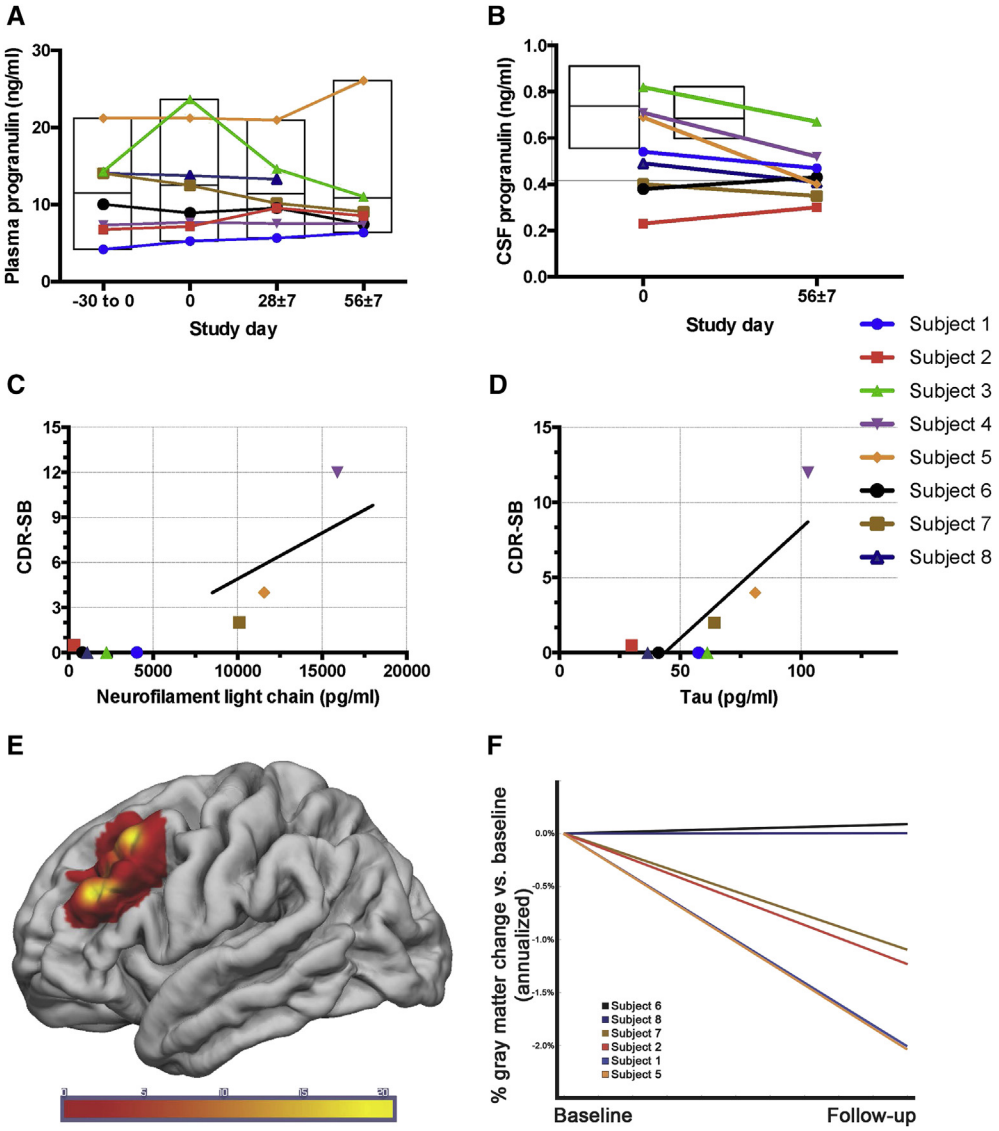

Fig. 1. Nimodipine had no effect on secondary outcome measures in humans, including plasma and CSF PGRN levels and brain volume loss. (A) The mean change in plasma PGRN between baseline (day 0) and the end of the trial (day 56 ± 7) was −1.47 ± 2.1 ng/mL. (B) The mean change in CSF PGRN between baseline (day 0) and the end of the trial (day 56 ± 7) was −0.09 ± 0.04 ng/mL. (C) Elevated neurofilament light chain correlated with disease severity. (P = .0002, Mann-Whitney) (D) Elevated tau correlated with disease severity (P = .0002, Mann-Whitney). (E) A significant cluster of gray matter loss was detected in the left middle frontal gyrus (yellow = 20% loss) (cluster extent of 1431 voxels, peak MNI coordinate: −51, 28, 28). (F) The change in brain volume loss was driven by symptomatic mutation carriers.

This is the second reported trial to be completed in *GRN* mutation carriers [7]. There are a number of therapeutic targets in the development pipeline intended for *GRN* mutation carriers, and this study provides a framework for future bench-to-bedside proof of mechanism studies for FTD-GRN.

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Study concept and design: A.L.B., L.G., S.J.S.

Acquisition, analysis, or interpretation of data: A.L.B., L.G., W.S., S.J.S., Z.A.M., S.-w.M., Y.Z., L.L.M., J.B., M.K., R.T., M.S., A.M.F., and K.E.F.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.trci.2017.08.002.

RESEARCH IN CONTEXT

1. Systematic review: The authors reviewed the literature using traditional (e.g., PubMed) sources. Heterozygous loss of function mutations in the progranulin gene (*GRN*) lead to frontotemporal dementia (FTD) through decreased production of the normal progranulin protein (PGRN). Therapeutic approaches have focused on finding novel compounds that increase PGRN levels. In murine model systems, calcium channel blockers were discovered to increase PGRN levels. We launched a phase 1 trial of nimodipine in *GRN* mutation carriers to test safety and tolerability.
2 Interpretation: Nimodipine was safe and well tolerated but is unlikely to provide therapeutic benefit in *GRN* FTD.
3. Future directions: This trial demonstrated that a nimble, small-scale trial could arise entirely from, and be contained within, an academic center. From the initial target identification to the execution of human trials, this trial provides a framework for future bench-to-bedside proof of mechanism studies in FTD.

References

[1] Cruts M, Gijselinck I, van der Zee J, Engelborghs S, Wils H, Pirici D, et al. Null mutations in progranulin cause ubiquitin-positive frontotemporal dementia linked to chromosome 17q21. Nature 2006;442:920–4.
[2] Gass J, Cannon A, Mackenzie IR, Boeve B, Baker M, Adamson J, et al. Mutations in progranulin are a major cause of ubiquitin-positive frontotemporal lobar degeneration. Hum Mol Genet 2006;15:2988–3001.
[3] Baker M, Mackenzie IR, Pickering-Brown SM, Gass J, Rademakers R, Lindholm C, et al. Mutations in progranulin cause tau-negative frontotemporal dementia linked to chromosome 17. Nature 2006;442:916–9.
[4] Cenik B, Sephton CF, Dewey CM, Xian X, Wei S, Yu K, et al. Suberoylanilide hydroxamic acid (vorinostat) up-regulates progranulin transcription: rational therapeutic approach to frontotemporal dementia. J Biol Chem 2011;286:16101–8.
[5] Holler CJ, Taylor G, McEachin ZT, Deng Q, Watkins WJ, Hudson K, et al. Trehalose upregulates progranulin expression in human and mouse models of GRN haploinsufficiency: a novel therapeutic lead to treat frontotemporal dementia. Mol Neurodegener 2016;11:46.
[6] Capell A, Liebscher S, Fellerer K, Brouwers N, Willem M, Lammich S, et al. Rescue of progranulin deficiency associated with frontotemporal lobar degeneration by alkalizing reagents and inhibition of vacuolar ATPase. J Neurosci 2011;31:1885–94.
[7] Alberici A, Archetti S, Pilotto A, Premi E, Cosseddu M, Bianchetti A, et al. Results from a pilot study on amiodarone administration in monogenic frontotemporal dementia with granulin mutation. Neurol Sci 2014;35:1215–9.
[8] Meeter LH, Patzke H, Loewen G, Dopper EG, Pijnenburg YA, van Minkelen R, et al. Progranulin levels in plasma and cerebrospinal fluid in granulin mutation carriers. Dement Geriatr Cogn Dis Extra 2016;6:330–40.
[9] Feneberg E, Steinacker P, Volk AE, Weishaupt JH, Wollmer MA, Boxer A, et al. Progranulin as a candidate biomarker for therapeutic trial in patients with ALS and FTLD. J Neural Transm (Vienna) 2016;123:289–96.
[10] Lopez-Arrieta JM, Birks J. Nimodipine for primary degenerative, mixed and vascular dementia. Cochrane Database Syst Rev 2002;CD000147.
[11] Bettcher BM, Wilheim R, Rigby T, Green R, Miller JW, Racine CA, et al. C-reactive protein is related to memory and medial temporal brain volume in older adults. Brain Behav Immun 2012;26:103–8.
[12] Ashburner J, Ridgway GR. Symmetric diffeomorphic modeling of longitudinal structural MRI. Front Neurosci 2012;6:197.
[13] Pankov A, Binney RJ, Staffaroni AM, Kornak J, Attygalle S, Schuff N, et al. Data-driven regions of interest for longitudinal change in frontotemporal lobar degeneration. Neuroimage Clin 2016;12:332–40.
[14] Whitwell JL, Weigand SD, Gunter JL, Boeve BF, Rademakers R, Baker M, et al. Trajectories of brain and hippocampal atrophy in FTD with mutations in MAPT or GRN. Neurology 2011;77:393–8.
[15] Minami SS, Min SW, Krabbe G, Wang C, Zhou Y, Asgarov R, et al. Progranulin protects against amyloid beta deposition and toxicity in Alzheimer's disease mouse models. Nat Med 2014;20:1157–64.
[16] Rascovsky K, Hodges JR, Knopman D, Mendez MF, Kramer JH, Neuhaus J, et al. Sensitivity of revised diagnostic criteria for the behavioural variant of frontotemporal dementia. Brain 2011;134:2456–77.
[17] Boeve BF, Lang AE, Litvan I. Corticobasal degeneration and its relationship to progressive supranuclear palsy and frontotemporal dementia. Ann Neurol 2003;54:S15–9.
[18] Gorno-Tempini ML, Hillis AE, Weintraub S, Kertesz A, Mendez M, Cappa SF, et al. Classification of primary progressive aphasia and its variants. Journal 2011;76:1006–14.
[19] Coppola G, Karydas A, Rademakers R, Wang Q, Baker M, Hutton M, et al. Gene expression study on peripheral blood identifies progranulin mutations. Ann Neurol 2008;64:92–6.