Prion protein quantification in cerebrospinal fluid as a tool for prion disease therapeutic development

Sonia M Vallabh[1,2,3], Chloe K Nobuhara[4], Franc Llorens[5], Inga Zerr[5], Piero Parchi[6,7], Sabina Capellari[6,8], Eric Kuhn[9], Jacob Klickstein[4], Jiri Safar[10], Flavia Nery[4], Kathryn Swoboda[4], Stuart L Schreiber[1], Michael D Geschwind[11], Henrik Zetterberg[12,13,14,15], Steven E Arnold[4], Eric Vallabh Minikel[1,2,3]

1. Center for the Science of Therapeutics, Broad Institute of MIT and Harvard, Cambridge, MA, 2142, USA
2. Program in Biological and Biomedical Sciences, Harvard Medical School, Boston, MA, 2115, USA
3. Prion Alliance, Cambridge, MA, 2139, USA
4. Department of Neurology, Massachusetts General Hospital, Boston, MA, 2114, USA
5. National Reference Center for TSE, Georg-August University, Göttingen, 37073, Germany
6. IRCCS - Institute of Neurological Sciences, Bologna, 40139, Italy
7. Department of Experimental, Diagnostic and Specialty Medicine, University of Bologna, Bologna, 40123, Italy
8. Department of Biomedical and Neuromotor Sciences, University of Bologna, Bologna, 40138, Italy
9. Proteomics Platform, Broad Institute of MIT and Harvard, Cambridge, MA, 2142, USA
10. National Prion Disease Pathology Surveillance Center, Case Western Reserve University, Cleveland, OH, 44106, USA
11. Memory and Aging Center, University of California San Francisco, San Francisco, CA, 94158, USA
12. Department of Psychiatry and Neurochemistry, the Sahlgrenska Academy at the University of Gothenburg, S-431 80 Mölndal, Sweden
13. Clinical Neurochemistry Laboratory, Sahlgrenska University Hospital, S-431 80 Mölndal, Sweden
14. UK Dementia Research Institute at UCL, London WC1N 3BG, United Kingdom
15. Department of Molecular Neuroscience, UCL Institute of Neurology, Queen Square, London WC1N 3BG, United Kingdom

†To whom correspondence should be addressed: svallabh@broadinstitute.org

Abstract

Reduction of native prion protein (PrP) levels in the brain is an attractive and genetically validated strategy for the treatment or prevention of human prion diseases. Development of any PrP-reducing therapeutic will require an appropriate pharmacodynamic biomarker: a practical and robust method for quantifying PrP, and reliably demonstrating its reduction, in the CNS of a living patient. Here we evaluate the potential of enzyme-linked immunosorbent assay (ELISA)-based quantification of human PrP in human cerebrospinal fluid (CSF) to serve as a biomarker for PrP-reducing therapeutics. We show that CSF PrP is highly sensitive to plastic adsorption during handling and storage, but its loss can be minimized by addition of detergent. We find that blood contamination does not affect CSF PrP levels, and CSF PrP and hemoglobin are uncorrelated, together suggesting that CSF PrP is CNS-derived, supporting its relevance for monitoring the tissue of interest and in keeping with high PrP abundance in brain relative to blood. In a cohort with controlled sample handling, CSF PrP exhibits good test-retest reliability (mean coefficient of variation 13% over 8-11 weeks), suggesting that therapeutically meaningful reductions in brain PrP could be readily detected in CSF. Together, these findings supply a method for monitoring the effect of a PrP-reducing drug in the CNS, which will be critical to the development of any prion therapeutic with this mechanism of action.

Introduction

Prion disease — a fatal and untreatable neurodegenerative disease — is caused by misfolding of the prion protein (PrP), encoded by the gene *PRNP*[1]. PrP is a well-validated drug target for prion disease: knockout animals are invulnerable to prion infection[2], heterozygous knockouts have delayed onset of disease[3], and post-natal depletion of PrP can delay or prevent prion disease[4,5]. Total knockout is tolerated in mice[6,7], cows[8], and goats[9,10], and healthy humans with one loss-of-function allele of *PRNP* have been identified[11]. Therefore, candidate therapies for prion disease may seek to lower PrP levels in the brain.

Clinical trials of such therapies will be enhanced by early determination of whether PrP is indeed being lowered effectively at a tolerated dose. The brain is the only tissue with a known phenotype in prion disease, and is therefore the target tissue for any therapeutic, but it is not realistic to perform serial brain biopsies to quantify PrP in brain tissue. Instead cerebrospinal fluid (CSF), produced in the brain by the choroid plexus and obtainable through a lumbar puncture (LP), provides a reasonable alternative. CSF is reasonably accessible in living patients and more reflective of the CNS milieu than peripheral tissues or fluids. PrP is known to be detectable in CSF at levels ranging from tens to hundreds of ng/mL, within the range of standard protein detection assays including the commonly used BetaPrion Human ELISA assay[12,13]. Here, we chart the technical parameters of this assay, and use it to establish the technical and biological suitability of CSF PrP as a pharmacodynamic biomarker for PrP-reducing therapeutics.

Results

1. The BetaPrion Human PrP ELISA quantifies total CSF PrP reproducibly, precisely, sensitively and selectively.

Multiple groups have reported successful detection of PrP in human CSF using ELISA assays, including the one currently commercially available human PrP ELISA kit, the BetaPrion ELISA assay[12–16]. This sandwich ELISA is configured in 96-well format and relies on an apparently conformational human PrP (HuPrP) capture antibody and a horseradish peroxidase (HRP)-conjugated primary detection antibody to HuPrP residues 151-180[13]. The assay is best described as measuring total PrP, which is the variable of interest for PrP-lowering therapeutics (see Discussion).

The standard of validation required for a ligand-binding assay to be used in the context of clinical drug development is more stringent than for a research context, as described in FDA's 2013 Draft Guidance on Bioanalytical Method Validation[17]. To this end, we assessed this assay's precision, sensitivity, selectivity and reproducibility by analyzing *N*=225 human CSF samples from symptomatic prion disease patients, pre-symptomatic prion disease mutation carriers, non-prion dementia patients, and normal pressure hydrocephalus (NPH) patients as well as controls (Table S1) across 41 plates. The results broadly support the technical suitability of this assay for reliable quantification of CSF PrP (Table 1 and Figure S1).

In assessing within-plate variability we discerned plate position effects for control samples, with a downward trend from upper left to lower right, suggesting that samples intended to be compared should be co-located on the ELISA plate, and/or that plate position should be

adjusted for using standard curves or control samples (Figure S2). Comparison of the kit standard curve to a standard curve made from recombinant human prion protein quantified by amino acid analysis (AAA) suggests that the kit may be most useful for relative rather than absolute quantification of PrP (Figure S3B).

Experiment	Results
Within-plate technical replicate reproducibility (same dilution)	CV = 8%
Within-plate technical replicate reproducibility (all dilutions)	CV = 11%
Between-plate technical replicate reproducibility	CV = 22% in control sample v1205.6 across 6 plates run on different days.
Sensitivity	LLOQ is 3-5× the blank signal, depending on the platereader used.
Selectivity	Non-reactive for recombinant mouse PrP, rat CSF and cynomolgus monkey CSF (consistent with one amino acid mismatch in the reported detection antibody epitope[13]), artificial CSF and protease-digested CSF.
Dilution linearity	Linear across two samples and five dilutions. See figure S1A.
Spike recovery	Using AAA-quantified recombinant HuPrP23-230 as a standard, spike recovery of recombinant PrP in CSF was 90% across five concentrations. Titration of a high PrP CSF sample into a low PrP sample resulted in linear recovery. See Figure S3.
Standard curve reproducibility	CV < 10% at all six non-zero standard curve points, across five replicates. See Figure S1.

Table 1. The BetaPrion human PrP ELISA assay technically supports reliable quantification of PrP in human CSF.

2. Standardized storage and handling are essential to reliable quantification of CSF PrP.

Consistent with previous reports, we observed over two orders of magnitude of variability of CSF PrP levels between samples (Fig S4A). Despite this large range, PrP was measurable by ELISA in all CSF samples analyzed, including in CSF from individuals with 13 different prion disease mutations (Fig S4A-B, Table 1). PrP was reduced in individuals with symptomatic prion disease, as previously reported[12–14,16,18], but still varied by approximately an order of magnitude within any one diagnosis (Fig S4A). PrP also differed significantly between the various cohorts included in our study (Fig S4B), but the variance within cohorts was dramatic (mean ~30-fold difference between highest and lowest sample within a cohort). CSF PrP was correlated with age (Fig S4C), but among our samples age is confounded with cohort, diagnosis, and likely many unobserved variables, making it unclear whether this correlation is biologically meaningful. CSF PrP did not differ according to sex (Fig S4D), and exhibited no lumbar-thoracic gradient (Fig S4E). After noticing that PrP levels appeared lower in smaller aliquots of the same CSF sample (Fig S5A), we hypothesized that differences in sample handling might be a major source of variability in observed CSF PrP levels.

CSF PrP's stability under different handling conditions has not previously been systematically assessed, but it is known that other neurodegenerative disease-associated amyloidogenic proteins have a high affinity for plastics[19,20]. To assess PrP's susceptibility to differential CSF sample handling, we subjected aliquots of a single CSF sample to variations in storage temperature, number of freeze-thaw cycles, storage aliquot size, number of transfers between polypropylene storage tubes, and amount of exposure to polypropylene pipette tips (Figure 1A). Strikingly, increased plastic exposure in the latter three conditions dramatically reduced measurable PrP in solution (Figure 1A). To promote PrP solubility in our samples, we experimented with adding small amounts of CHAPS, a common zwitterionic surfactant known to enhance protein solubility in multiple contexts[21–23]. Addition of 0.03% CHAPS prior to aliquotting minimized PrP loss to plastic across most manipulations (Figure 2A). For instance, transferring a CSF sample to a new microcentrifuge tube three times eliminated at least 73% of detectable PrP ($P < 1 \times 10^{-6}$, two-sided t test) without CHAPS, but only 7.1% ($P = 0.37$) of PrP was lost in the presence of 0.03% CHAPS. Addition of CHAPS also increased total PrP recovery, presumably by preventing loss to the single polypropylene tube and tips used for plating samples (Figure S5), and was effective against loss to multiple plastics but not glass (Figure 1C).

Storing CSF at room temperature for 24 hours and subjecting samples to three freeze-thaw cycles reduced PrP even in the presence of detergent (Figure 1A-B). From this we conclude that time at room temperature and number of freeze-thaw cycles for CSF samples should be a) minimized, b) closely tracked for all samples, and c) standardized for samples across which PrP levels will be compared.

We also investigated the relationship between measured PrP and total protein in N=217 samples, using the DC total protein assay. Across all samples analyzed, a modest correlation ($r = 0.36$, Spearman rank test, $P = 6.2 \times 10^{-8}$) between PrP and total protein was observed, which may reflect either a biological phenomenon, or simply the ability of higher ambient protein levels to serve a blocking function that partially offsets PrP loss by adsorption. In support of the latter interpretation, addition to CSF of 1 mg/mL bovine serum albumin increased recovery of PrP (Figure S5F), though it was less effective than CHAPS at preventing loss due to transfers.

Overall, these data emphasize the importance of consistent handling of CSF samples intended for comparative PrP quantification, and support preventative addition of detergent as a means to prevent otherwise massively confounding PrP loss to storage and handling surfaces (see Discussion).

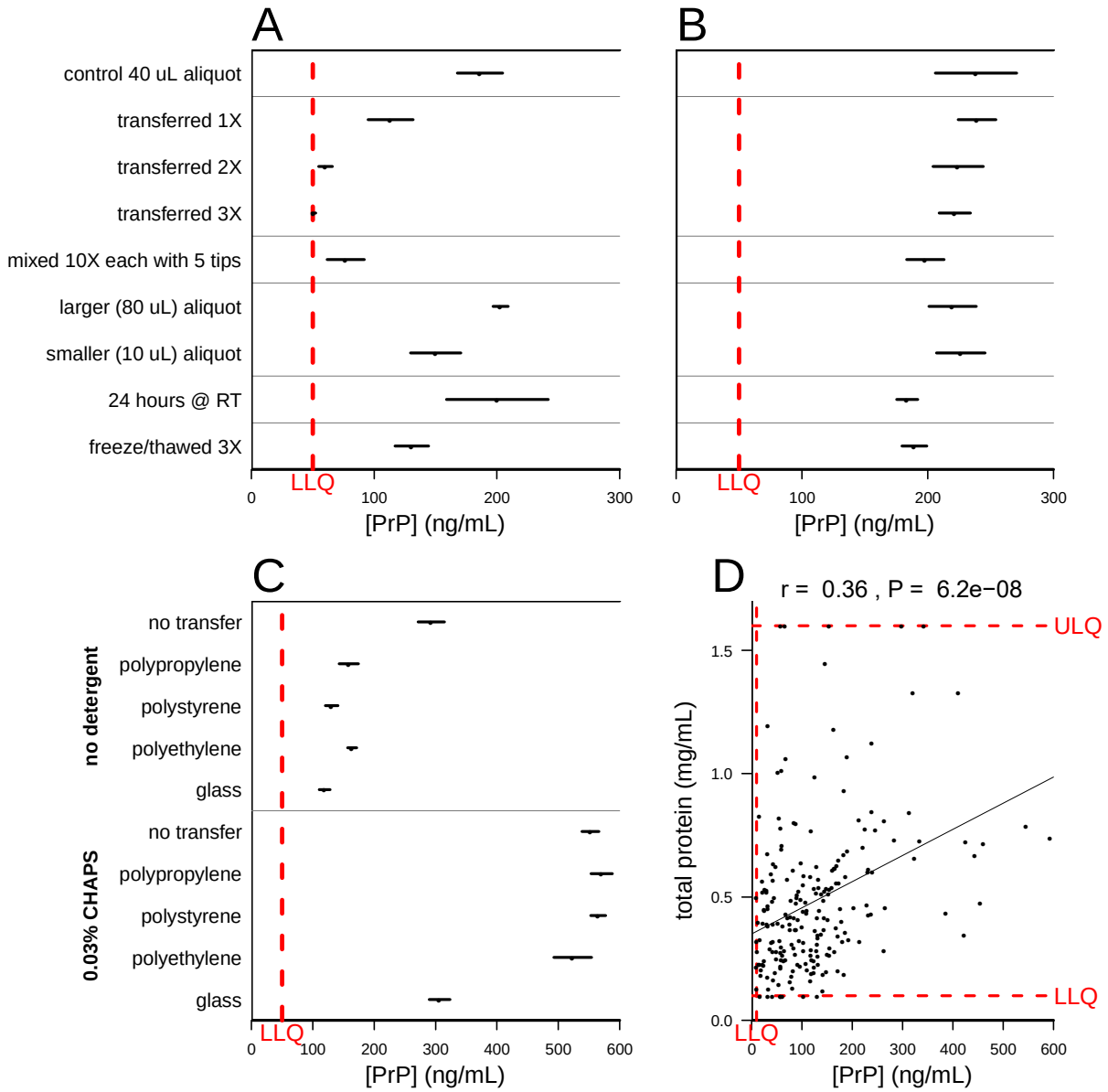

Figure 1. Storage and handling can dramatically reduce the amount of PrP detected in CSF samples unless appropriate measures are taken. *A. Increased polypropylene exposure substantially reduces detectable PrP. B. Addition of 0.03% CHAPS detergent to samples increases PrP recovery and consistently mitigates PrP loss to plastic. C. Addition of CHAPS (bottom) increases total PrP recovery and shows similar rescue across plastics, but substantial PrP loss is still observed upon storage in glass. D. Across 217 CSF samples, total protein levels and PrP levels were modestly correlated (Spearman's rank correlation coefficient = 0.36, P=6.2×10^{-8}). In A-C, dots represent mean and line segments represent 95% confidence intervals across 4 to 7 aliquots of the same sample, each measured in duplicate at a 1:50 dilution. In D, dots represent mean of measurements within dynamic range, among 2 dilutions with 2 technical replicates each.*

3. PrP in CSF is CNS-derived and unlikely to be confounded by blood contamination.

CSF PrP is an informative tool in prion disease only insofar as it is a faithful proxy for PrP levels in the CNS, the relevant target for any future therapeutic including those with a PrP-lowering mechanism. CSF proteins derive from two major sources, CNS and blood, with proportional contribution driven by relative tissue abundance of a given protein[24]. Blood proteins enter CSF either through the trauma of lumbar puncture or through gradual diffusion through the dura as CSF flows down the spinal canal[25,26]. To assess the contribution of blood-derived PrP to overall CSF PrP, we compared PrP levels across brain samples and red blood cell, buffy coat and plasma fractions of blood from non-neurodegenerative disease control individuals, versus all of the CSF samples in our study (Figure 2A). Among blood fractions, PrP was most consistently detected in buffy coat, in keeping with reports that blood PrP emanates chiefly from platelets[27,28]; we also detected PrP above the lower limit of quantification in some red cell samples, but never in plasma. As the average PrP concentration in all three blood fractions was still well below that in brain and was lower than that in 96% of CSF samples analyzed, the risk of confounding signal from blood-derived PrP appears negligible. Consistent with this conclusion, spiking whole blood into CSF at up to 1% (v/v) did not increase the detected PrP (Figure 2B). Finally, as a proxy for blood contamination we measured hemoglobin levels in N=128 CSF samples and observed no correlation between CSF hemoglobin and CSF PrP (Figure 2C). Variation in hemoglobin levels also failed to confound the test-retest reliability of CSF PrP (Figure S6). From these lines of evidence we conclude that the PrP detected in CSF is overwhelmingly derived from the CNS.

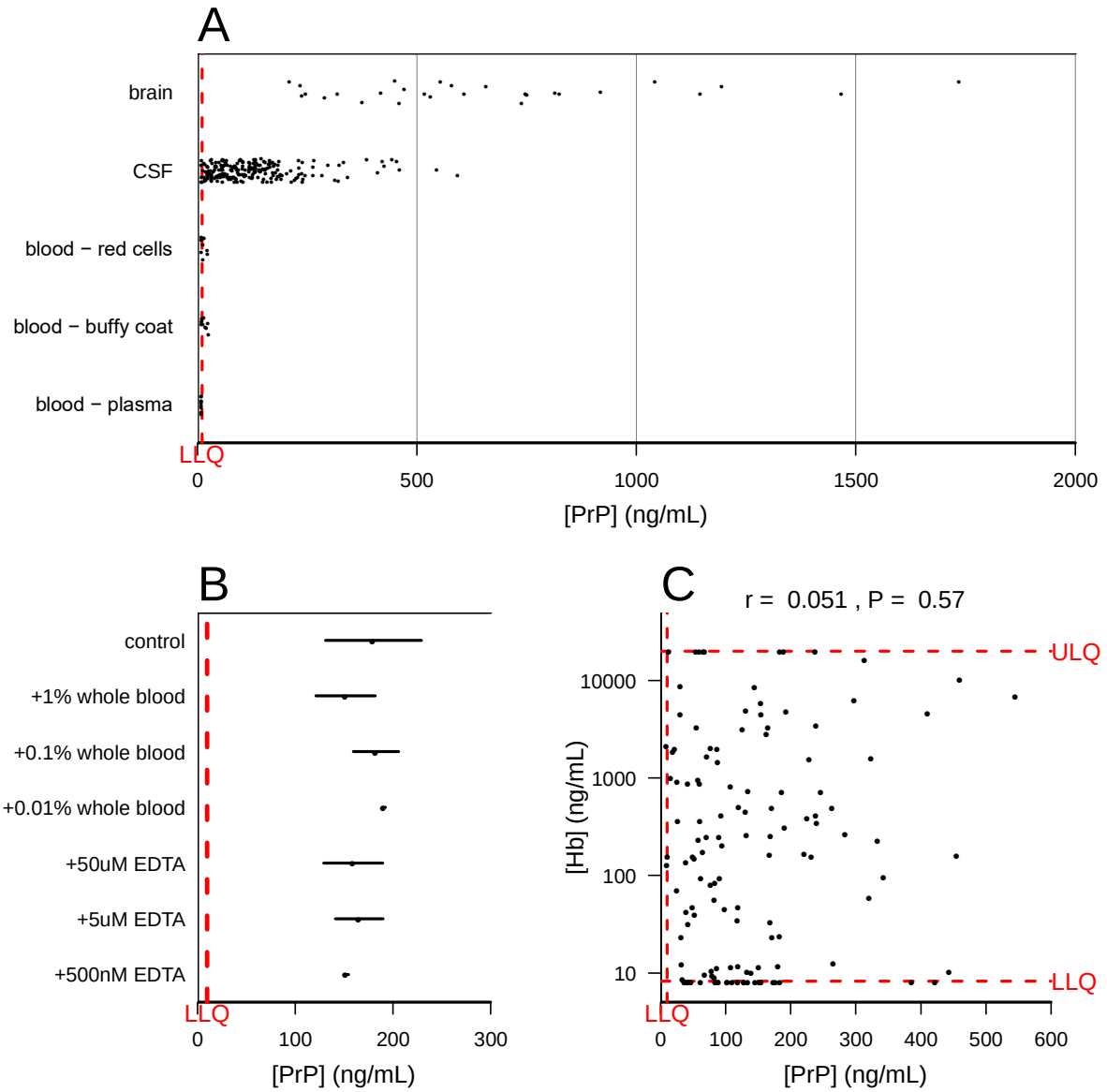

Figure 2. Blood PrP contributes negligibly to the PrP detected in CSF. *A. PrP is abundant in a range of human brain regions, undetectable in human plasma, and is detectable in the red cell and buffy coat fractions only at low levels compared to PrP in CSF. B. Spiking whole blood into CSF up to 1% by volume does not impact measured PrP. C. Hemoglobin and PrP levels in CSF are uncorrelated. In A and C, dots represent mean of measurements within dynamic range, among 2 technical replicates per dilution. In A-C, dots represent mean and line segments represent 95% confidence intervals across 2 to 3 aliquots of the same sample.*

4. CSF PrP is stable on test-retest.

Across *N*=225 samples analyzed, CSF PrP levels ranged over two orders of magnitude (1.9 – 593.6 ng/mL), consistent with previous reports[12,13], but our findings above (Figure 1) suggest that much variability might arise from differences in sample handling. In order for CSF PrP levels to serve as a meaningful biomarker, they must be stable enough in one individual over

time that a drug-dependent reduction could be reliably detected. We quantified PrP in test-retest CSF samples collected from nine individuals — placebo-treated controls with non-prion dementia — who had undergone two fasting morning lumbar punctures at 8-11 week intervals in the context of a clinical trial[29]. LPs were performed according to a standardized protocol by a single investigator, and samples were subsequently processed uniformly. Under these highly controlled conditions, the mean CV between timepoints for a given participant was agreeably low at 13% (Figure 3). Higher CVs of 33% - 41% were observed in three other cohorts where sample handling appears to have been less uniform (Supplementary Discussion and Figure S7).

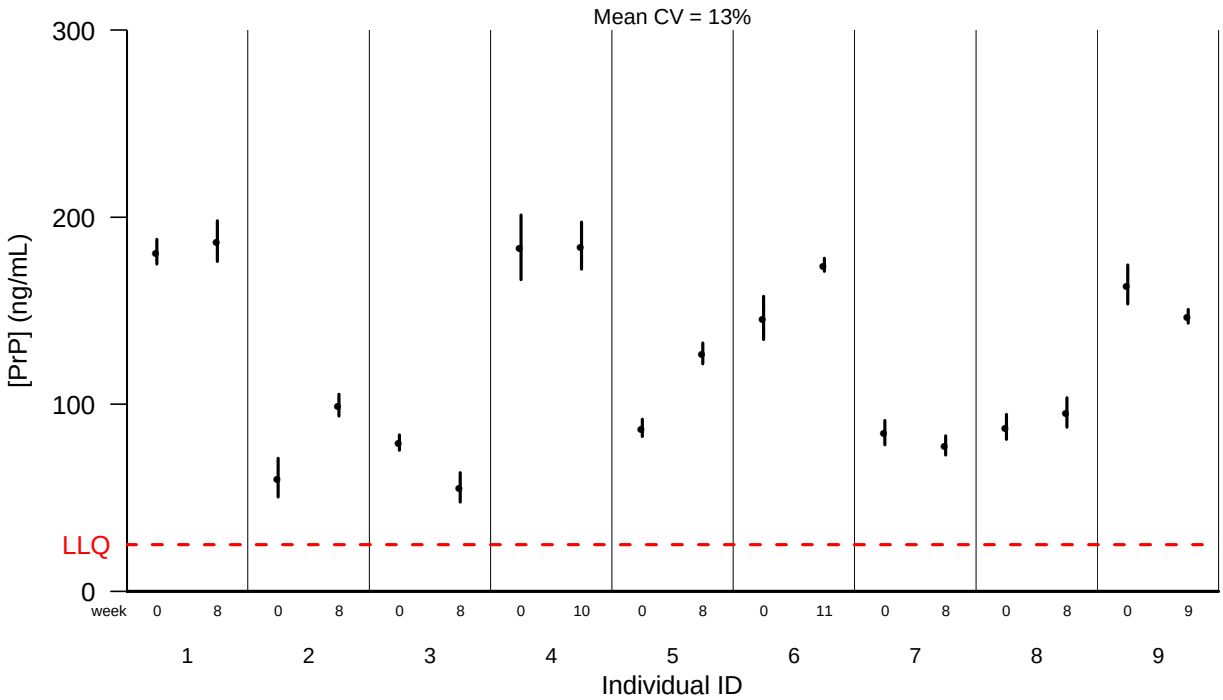

Figure 3. Test-retest stability of CSF PrP. *Uniformly processed CSF samples were provided from a past clinical trial, from placebo-treated individuals with mild, non-prion cognitive impairment. Fasting morning lumbar punctures were performed by one investigator on nine individuals then repeated at an interval of 8-11 weeks. Dots represent means, and line segments 95% confidence intervals, of measurements within dynamic range among 2 dilutions with 2 technical replicates each.*

Discussion

Here we present evidence supporting CSF PrP quantification as a tool for clinical trials of PrP-lowering therapeutics. We establish that CSF PrP is sensitive to multiple factors that may be encountered during handling and processing, and that the addition of 0.03% CHAPS detergent mitigates the most dramatic such factor by minimizing PrP loss to plastic. With use of appropriate protocols, CSF PrP can be measured reproducibly and with favorable test-retest reliability, with a mean CV of 13% over 8-11 weeks in one cohort. CSF PrP is CNS-derived, rather than blood-derived, suggesting it should change in response to lowering of PrP in the brain.

The above attributes suggest that CSF PrP will be a useful pharmacodynamic biomarker in the development of PrP-lowering therapeutics. However, our findings regarding PrP's sensitivity to handling and processing factors demonstrate that an optimized protocol for CSF collection and processing will need to be closely followed for samples to be meaningfully compared. To this end, the protocol we are now using to collect such samples is detailed in Figure S8. For maximum protection of PrP from plastic adsorption, we propose addition of 0.03% CHAPS immediately upon transfer of CSF from the initial lumbar puncture syringe, prior to aliquotting or freezing. Detergent type and level were chosen for compatibility with our downstream ELISA and mass spectrometry assays. As shown in Figure S8, we are reserving aliquots of CSF without additive for future use in detergent-incompatible assays, but do not recommend use of such aliquots for PrP quantification.

As previously mentioned, PrP levels in CSF as measured by ELISA have been reported to be reduced by on the order of half in symptomatic prion disease patients[12,13,16], and this phenomenon is reflected in our samples as well (Figure S4). Multiple plausible biological mechanisms could explain these findings: incorporation of PrP into insoluble plaques[30,31], internalization of misfolded PrP in the endosomal-lysosomal pathway[32], and post-translational downregulation of PrP as a function of disease[33]. It is therefore possible that an intrinsic reduction in CSF PrP in the course of symptomatic disease could confound the use of PrP as a biomarker for the activity of PrP-lowering drug tested in a symptomatic population. While it is important to be aware of this potential limitation, symptomatic patients are not the population most in need of such a biomarker, as other tools exist to assess drug activity and efficacy in symptomatic patients. In particular, the signature rapid clinical decline associated with active disease has enabled several previous clinical trials to be conducted in symptomatic cohorts based on cognitive or survival endpoints[34–40]. Instead, the population best positioned to benefit from a CSF PrP pharmacodynamic biomarker in conjunction with a PrP-lowering drug is the population of presymptomatic individuals carrying high-penetrance genetic prion disease mutations. Our experiments to date confirm that PrP is measurable in carriers across a variety of mutations.. Our observations here support the hypothesis that target engagement and achievement of a meaningful proximal biological effect by a PrP-lowering drug candidate could be observed through quantification of PrP in CSF from serial lumbar punctures in such individuals, a hypothesis that will need to be tested in a clinical trial once such a drug candidate is available.

Our study has several limitations. First, ELISA relies upon two epitopes being present and properly folded, and is thus vulnerable to confounding from misfolding or native proteolytic events. We are presently working to develop a targeted mass spectrometry-based orthogonal method for CSF total PrP quantification. Second, although we have established that CSF PrP is quantifiable in genetic prion disease patients and has good test-retest reliability in a cohort of patients with non-prion dementia, when we embarked on the present study we did not have access to short-term test-retest samples from presymptomatic genetic prion disease patients. To address this shortfall, in summer 2017 we launched a clinical research study at Massachusetts General Hospital to recruit presymptomatic individuals with *PRNP* mutations, and controls, for two lumbar punctures at an 8- to 16-week interval[41]. This study is following the collection and processing protocol specified in Figure S8. We hypothesize that with this protocol in place, test-retest reliability in this population will prove sufficient to enable future clinical trials monitoring CSF PrP before and after administration of a PrP-lowering drug. Third, the samples analyzed here were re-used after collection for other research or clinical purposes, meaning that in most cases we cannot fully account for how the samples were handled prior to our receipt of them. Thus, our numbers may exaggerate the inter-individual variation in CSF PrP in the

population. The question of whether the large observed inter-individual variability in PrP CSF levels indicates true biological variability or handling artifacts will be addressed by the uniformly processed samples currently being collected through our clinical study.

In recent studies of proposed Alzheimer's disease and Huntington's disease biomarkers, the goal has been detection of a pathological molecule such as Aβ oligomers or mutant Huntingtin protein that is thought to be causative or indicative of the disease process[20,42]. Our goal differs in that native PrP is present in all humans, and is not itself a pathogenic species indicative of disease; it is present and measurable in healthy individuals. PrP is an attractive drug target in prion disease because it is shared among all prion disease subtypes, unifying what are otherwise ultra-orphan subsets of an already rare disease. Unlike the misfolded prions that derive from PrP and ultimately act as the pathogen in prion disease, PrP is structurally well-characterized and can be targeted genetically; approaches to protectively reducing its levels could intervene at the level of DNA, RNA or protein. Our findings should empower clinical development towards the overdue realization of this well-supported therapeutic hypothesis.

Moreover, this biomarker may help to empower a heretofore-unexplored route for drug development and trials in healthy, at-risk individuals. The increasing availability of large genetic datasets is enabling ever-more-refined estimates of the penetrance associated with disease-associated *PRNP* mutations[11]. Individuals facing 90% or greater lifetime risk of genetic prion disease can be reliably identified years or decades in advance of onset. Such carriers lack any overt phenotype, and to date no reliable change indicative of prodromal disease has been systematically detected in this population by imaging or biochemical analysis. In addition, even if such a marker were to be found, it would be useful only once the prodromal disease process were already underway, when the greatest opportunity for meaningful intervention in at-risk individuals may have already passed. Preclinical evidence strongly indicates that regardless of mechanism of action, the potency of anti-prion therapeutics scales with time of intervention relative to disease course, with prophylactic administration prior to any molecular pathology offering greater benefit in delaying disease[43–46]. In the context of prevention trials in healthy carriers, it is possible that CSF PrP will be critical not just as a marker of target engagement, but as a surrogate endpoint. Because following pre-symptomatic individuals to a clinical endpoint appears infeasible[47], lowering CSF PrP has been proposed as a surrogate endpoint meriting Accelerated Approval[48]. Continued study of CSF PrP will be critical to steering future treatment trials towards a preventative paradigm and to honoring the precious opportunity for preemptive intervention provided by predictive genetic testing.

Methods

Cerebrospinal fluid samples. De-identified human CSF samples were provided by multiple clinical collaborators and included both unpublished and previously published cohorts[29,49]. Samples were shipped on dry ice and stored at -80°C. Prior to use, samples were thawed on ice and centrifuged at 2,000 × g (at 4°C). Ninety percent of the volume was pipetted into a new tube to separate supernatant from cellular or other debris, aliquotted into new polypropylene storage tubes and refrozen at -80°C. For indicated samples, 0.03% CHAPS detergent by volume (final concentration) was pre-loaded into the supernatant receiving tube prior to the post-centrifugation transfer, then mixed into the sample by gentle pipetting prior to aliquotting.

Quantification of human PrP in CSF, brain tissue and blood using the BetaPrion human PrP ELISA kit. Across experiments, PrP was quantified using the BetaPrion human PrP ELISA kit (Analytik Jena, cat no. 847-0104000104) according to the manufacturer's instructions. In brief, samples were diluted into blocking buffer (5% BSA and 0.05% Tween-20 in PBS, filtered prior to use) at concentrations ranging from 1:100 to neat depending on the anticipated PrP content of the sample type. Unknown CSF samples were run at two dilutions each (typically 1:10 and 1:50). Only one out of 225 CSF samples analyzed fell below the range of the assay's lower limit of detection (1 ng/mL) at a 1:10 dilution, and was re-run neat, yielding a result of 1.9 ng/mL. Human brain samples were obtained from the Massachusetts Alzheimer's Disease Research Center (ADRC; *N*=26 samples from 5 different individuals, representing diverse cortical and subcortical regions) and from the National Prion Disease Pathology Surveillance Center (*N*=2 samples of frontal cortex from non-prion controls) homogenized in PBS with 0.03% CHAPS at 10% weight/vol in 7mL tubes (Precellys no. KT039611307.7) using a MiniLys tissue homogenizer (Bertin no. EQ06404-200-RD000.0) for 3 cycles of 40 seconds at maximum speed. The resulting 10% brain homogenates were diluted 1:10 and 1:100 in blocking buffer for ELISA.
Human blood fractions were obtained from Zen-Bio, 0.03% CHAPS was added, and samples were then mixed either by pipetting up and down or by homogenization in a MiniLys using the same protocol described above. Blood fractions were diluted 1:10 in blocking buffer for ELISA. All samples were plated in duplicate. Lyophilized standards and kit reagents were diluted fresh for same-day use, with the exception of wash buffer and blocking buffer, excess of which were stored at 4°C for reuse within 4 weeks. The assay format is 96-well comprised of twelve modular 8-well strips which enabled partial plates to be run in some cases. Following all add and incubation steps the absorption per well was read in either a SpectraMax or FluoStar Optima plate reader at 450 nm with 620 nm absorbance also monitored as baseline. Data was exported as a text file and analyzed in R.

Negative controls. Rat and cynomolgous monkey CSF (BioReclamation IVT; two samples each from two separate animals) and artificial CSF (Tocris no. 3525) were aliquotted and stored at -80°C. For protease-digested CSF, two CSF samples with 0.03% CHAPS (measured to contain 273 and 643 ng/mL PrP undigested) were digested with 5 ug/mL Proteinase K (WW Grainger Co. cat. no. 5000186667) at 37C for 1 hour, after which the digestion was halted with 4 mM PefaBloc (Sigma Aldrich cat. no. 11429868001) immediately prior to use in ELISA.

Recombinant prion protein purification. For spike-in experiments and attempted detection of mouse recombinant PrP, in-house purified recombinant full-length human prion protein and mouse prion protein were purified from *E. coli* using established vectors (a generous gift from Byron Caughey's laboratory at NIH Rocky Mountain Labs) according to established methods[50,51]. Protein concentration was determined by 280 nm absorbance on a NanoDrop, and by amino acid analysis (AAA) performed in duplicate (New England Peptide) after the addition of 0.03% CHAPS.

Storage and handling experiments. For all storage and handling experiments, each condition was run in parallel on four identical aliquots made from one original CSF sample, and each aliquot was plated in duplicate. For all transfer experiments, 40 µL CSF aliquots were thawed on ice, then the full volume was transferred to a new 500 µL storage tube the indicated number of times and allowed to sit for a minimum of fifteen minutes in each tube. Where not otherwise indicated, tubes were polypropylene.

Total protein assay. The DC total protein assay (Bio-Rad cat. no. 5000111) was used according to the manufacturer's instructions to measure total protein across 217 CSF samples. This

assay, similar in principle to a Lowry assay, combines the protein with an alkaline copper tartrate solution and Folin reagent[52]. The protein reacts with copper in the alkaline medium, then reduces the Folin reagent to yield species with a characteristic blue color in proportion to abundance of key amino acids including tyrosine and tryptophan.

Blood fractions. Red blood cell, buffy coat, and plasma separated blood fractions from three separate individuals (Zen-Bio) were thawed, aliquotted, and refrozen before use to ensure lysis of cellular fractions. The BetaPrion human PrP ELISA was used to compare PrP levels these three blood fractions, two control human postmortem brain homogenate samples, and 156 human CSF samples. Each sample was run in duplicate.

Whole blood spike-in. Human whole blood (Zen-Bio) was spiked into parallel aliquots of a single CSF sample containing baseline mid-range PrP at 1%, 0.1%, or 0.01% per volume. EDTA spike-ins were performed in parallel to control for EDTA preservative carried in the blood sample. Samples were refrozen following spike-in then re-thawed for use to ensure lysis of cellular fractions prior to PrP quantification.

Bethyl Laboratories Human Hemoglobin ELISA. Hemoglobin was quantified in 128 human CSF samples using the Human Hemoglobin ELISA kit (Bethyl Laboratories no. E88-134), according to the manufacturer's instructions. Samples were diluted 1:10 and 1:100 for most experiments, an in some cases 1:20 and 1:100. All samples were plated in duplicate.

Data and source code availability. All analyses were conducted using custom R scripts. Raw data from platereaders, associated metadata, and source code sufficient to reproduce the analyses reported herein are publicly available at https://github.com/ericminikel/csf_prp_quantification/

Acknowledgments

This study was approved by the Broad Institute's Office of Research Subjects Protection (ORSP-3587). SV is supported by the National Science Foundation (GRFP 2015214731). EVM is supported by the National Institutes of Health (F31 AI122592). We thank the Massachusetts Alzheimer's Disease Research Center (ADRC) and the MassGeneral Institute for Neurodegenerative Disease (MIND) Tissue Bank for providing human brain and cerebrospinal fluid samples for this study. We thank the patients and their families who contributed samples to this research.

References

1. Prusiner SB. Prions. Proc Natl Acad Sci. 1998 Nov 10;95(23):13363–13383. PMID: 9811807
2. Büeler H, Aguzzi A, Sailer A, Greiner RA, Autenried P, Aguet M, Weissmann C. Mice devoid of PrP are resistant to scrapie. Cell. 1993 Jul 2;73(7):1339–1347. PMID: 8100741
3. Büeler H, Raeber A, Sailer A, Fischer M, Aguzzi A, Weissmann C. High prion and PrPSc levels but delayed onset of disease in scrapie-inoculated mice heterozygous for a disrupted PrP gene. Mol Med Camb Mass. 1994 Nov;1(1):19–30. PMCID: PMC2229922
4. Mallucci G, Dickinson A, Linehan J, Klöhn P-C, Brandner S, Collinge J. Depleting Neuronal PrP in Prion Infection Prevents Disease and Reverses Spongiosis. Science. 2003 Oct 31;302(5646):871–874. PMID: 14593181
5. Safar JG, DeArmond SJ, Kociuba K, Deering C, Didorenko S, Bouzamondo-Bernstein E, Prusiner SB, Tremblay P. Prion clearance in bigenic mice. J Gen Virol. 2005 Oct;86(Pt 10):2913–2923. PMID: 16186247
6. Büeler H, Fischer M, Lang Y, Bluethmann H, Lipp HP, DeArmond SJ, Prusiner SB, Aguet M, Weissmann C. Normal development and behaviour of mice lacking the neuronal cell-surface PrP protein. Nature. 1992 Apr 16;356(6370):577–582. PMID: 1373228
7. Bremer J, Baumann F, Tiberi C, Wessig C, Fischer H, Schwarz P, Steele AD, Toyka KV, Nave K-A, Weis J, Aguzzi A. Axonal prion protein is required for peripheral myelin maintenance. Nat Neurosci. 2010 Mar;13(3):310–318. PMID: 20098419
8. Richt JA, Kasinathan P, Hamir AN, Castilla J, Sathiyaseelan T, Vargas F, Sathiyaseelan J, Wu H, Matsushita H, Koster J, Kato S, Ishida I, Soto C, Robl JM, Kuroiwa Y. Production of cattle lacking prion protein. Nat Biotechnol. 2007 Jan;25(1):132–138.
9. Yu G, Chen J, Xu Y, Zhu C, Yu H, Liu S, Sha H, Chen J, Xu X, Wu Y, Zhang A, Ma J, Cheng G. Generation of goats lacking prion protein. Mol Reprod Dev. 2009 Jan;76(1):3. PMID: 18951376
10. Benestad SL, Austbø L, Tranulis MA, Espenes A, Olsaker I. Healthy goats naturally devoid of prion protein. Vet Res. 2012;43(1):87. PMCID: PMC3542104
11. Minikel EV, Vallabh SM, Lek M, Estrada K, Samocha KE, Sathirapongsasuti JF, McLean CY, Tung JY, Yu LPC, Gambetti P, Blevins J, Zhang S, Cohen Y, Chen W, Yamada M, Hamaguchi T, Sanjo N, Mizusawa H, Nakamura Y, Kitamoto T, Collins SJ, Boyd A, Will RG, Knight R, Ponto C, Zerr I, Kraus TFJ, Eigenbrod S, Giese A, Calero M, Pedro-Cuesta J de, Haïk S, Laplanche J-L, Bouaziz-Amar E, Brandel J-P, Capellari S, Parchi P, Poleggi A, Ladogana A, O'Donnell-Luria AH, Karczewski KJ, Marshall JL, Boehnke M, Laakso M, Mohlke KL, Kähler A, Chambert K, McCarroll S, Sullivan PF, Hultman CM, Purcell SM, Sklar P, Lee SJ van der, Rozemuller A, Jansen C, Hofman A, Kraaij R, Rooij JGJ van, Ikram MA, Uitterlinden AG, Duijn CM van, (ExAC) EAC, Daly MJ, MacArthur DG. Quantifying prion disease penetrance using large population control cohorts. Sci Transl Med. 2016 Jan 20;8(322):322ra9-322ra9. PMID: 26791950
12. Meyne F, Gloeckner SF, Ciesielczyk B, Heinemann U, Krasnianski A, Meissner B, Zerr I. Total prion protein levels in the cerebrospinal fluid are reduced in patients with various neurological disorders. J Alzheimers Dis JAD. 2009;17(4):863–873. PMID: 19542614
13. Dorey A, Tholance Y, Vighetto A, et al. Association of cerebrospinal fluid prion protein levels and the distinction between alzheimer disease and creutzfeldt-jakob disease. JAMA Neurol. 2015 Mar 1;72(3):267–275.
14. Llorens F, Ansoleaga B, Garcia-Esparcia P, Zafar S, Grau-Rivera O, López-González I, Blanco R, Carmona M, Yagüe J, Nos C, del Río JA, Gelpí E, Zerr I, Ferrer I. PrP mRNA and protein expression in brain and PrPc in CSF in Creutzfeldt-Jakob disease MM1 and VV2. Prion. 2013 Sep 1;7(5):383–393. PMCID: PMC4134343
15. Schmitz M, Schlomm M, Hasan B, Beekes M, Mitrova E, Korth C, Breil A, Carimalo J, Gawinecka J, Varges D, Zerr I. Codon 129 polymorphism and the E200K mutation do not affect the cellular prion protein isoform composition in the cerebrospinal fluid from patients with Creutzfeldt–Jakob disease. Eur J Neurosci. 2010 Jun 1;31(11):2024–2031.
16. Abu Rumeileh S, Lattanzio F, Stanzani Maserati M, Rizzi R, Capellari S, Parchi P. Diagnostic Accuracy of a Combined Analysis of Cerebrospinal Fluid t-PrP, t-tau, p-tau, and Aβ42 in the Differential Diagnosis of Creutzfeldt-Jakob Disease from Alzheimer's Disease with Emphasis on Atypical Disease Variants. J Alzheimers Dis. 55(4):1471–1480. PMCID: PMC5181677

17. U.S. Food and Drug Administration. Guidance for Industry: Bioanalytical Method Validation [Internet]. 2013 Sep. Available from: https://www.fda.gov/downloads/drugs/guidancecomplianceregulatoryinformation/guidances/ucm368107.pdf
18. Torres M, Cartier L, Matamala JM, Hernández N, Woehlbier U, Hetz C. Altered Prion protein expression pattern in CSF as a biomarker for Creutzfeldt-Jakob disease. PloS One. 2012;7(4):e36159. PMCID: PMC3338608
19. Lewczuk P, Beck G, Esselmann H, Bruckmoser R, Zimmermann R, Fiszer M, Bibl M, Maler JM, Kornhuber J, Wiltfang J. Effect of Sample Collection Tubes on Cerebrospinal Fluid Concentrations of Tau Proteins and Amyloid β Peptides. Clin Chem. 2006 Feb 1;52(2):332–334. PMID: 16449222
20. Wild EJ, Boggio R, Langbehn D, Robertson N, Haider S, Miller JRC, Zetterberg H, Leavitt BR, Kuhn R, Tabrizi SJ, Macdonald D, Weiss A. Quantification of mutant huntingtin protein in cerebrospinal fluid from Huntington's disease patients. J Clin Invest. 2015 May 1;125(5):1979–1986.
21. Wetlaufer D b., Xie Y. Control of aggregation in protein refolding: A variety of surfactants promote renaturation of carbonic anhydrase II. Protein Sci. 1995 Aug 1;4(8):1535–1543.
22. Cladera J, Rigaud JL, Villaverde J, Duñach M. Liposome solubilization and membrane protein reconstitution using Chaps and Chapso. Eur J Biochem. 1997 Feb 1;243(3):798–804. PMID: 9057848
23. Hjelmeland LM, Chrambach A. [16] Solubilization of functional membrane proteins. Methods Enzymol. 1984 Jan 1;104:305–318.
24. Reiber H. Proteins in cerebrospinal fluid and blood: barriers, CSF flow rate and source-related dynamics. Restor Neurol Neurosci. 2003;21(3–4):79–96. PMID: 14530572
25. You J-S, Gelfanova V, Knierman MD, Witzmann FA, Wang M, Hale JE. The impact of blood contamination on the proteome of cerebrospinal fluid. Proteomics. 2005 Jan;5(1):290–296. PMID: 15672452
26. Aasebø E, Opsahl JA, Bjørlykke Y, Myhr K-M, Kroksveen AC, Berven FS. Effects of Blood Contamination and the Rostro-Caudal Gradient on the Human Cerebrospinal Fluid Proteome. PLOS ONE. 2014 Mar 5;9(3):e90429.
27. Barclay GR, Hope J, Birkett CR, Turner ML. Distribution of cell-associated prion protein in normal adult blood determined by flow cytometry. Br J Haematol. 1999 Dec;107(4):804–814. PMID: 10606888
28. MacGregor I, Hope J, Barnard G, Kirby L, Drummond O, Pepper D, Hornsey V, Barclay R, Bessos H, Turner M, Prowse C. Application of a time-resolved fluoroimmunoassay for the analysis of normal prion protein in human blood and its components. Vox Sang. 1999;77(2):88–96. PMID: 10516553
29. Koenig AM, Mechanic-Hamilton D, Xie SX, Combs MF, Cappola AR, Xie L, Detre JA, Wolk DA, Arnold SE. Effects of the Insulin Sensitizer Metformin in Alzheimer Disease: Pilot Data From a Randomized Placebo-controlled Crossover Study. Alzheimer Dis Assoc Disord. 2017 Jun;31(2):107–113. PMCID: PMC5476214
30. Roberts GW, Lofthouse R, Brown R, Crow TJ, Barry RA, Prusiner SB. Prion-protein immunoreactivity in human transmissible dementias. N Engl J Med. 1986 Nov 6;315(19):1231–1233. PMID: 3531867
31. Parchi P, Giese A, Capellari S, Brown P, Schulz-Schaeffer W, Windl O, Zerr I, Budka H, Kopp N, Piccardo P, Poser S, Rojiani A, Streichemberger N, Julien J, Vital C, Ghetti B, Gambetti P, Kretzschmar H. Classification of sporadic Creutzfeldt-Jakob disease based on molecular and phenotypic analysis of 300 subjects. Ann Neurol. 1999 Aug;46(2):224–233. PMID: 10443888
32. Caughey B, Raymond GJ, Ernst D, Race RE. N-terminal truncation of the scrapie-associated form of PrP by lysosomal protease(s): implications regarding the site of conversion of PrP to the protease-resistant state. J Virol. 1991 Dec;65(12):6597–6603. PMCID: PMC250721
33. Mays CE, Kim C, Haldiman T, van der Merwe J, Lau A, Yang J, Grams J, Di Bari MA, Nonno R, Telling GC, Kong Q, Langeveld J, McKenzie D, Westaway D, Safar JG. Prion disease tempo determined by host-dependent substrate reduction. J Clin Invest. 2014 Feb 3;124(2):847–858. PMCID: PMC3904628
34. Otto M, Cepek L, Ratzka P, Doehlinger S, Boekhoff I, Wiltfang J, Irle E, Pergande G, Ellers-Lenz B, Windl O, Kretzschmar HA, Poser S, Prange H. Efficacy of flupirtine on cognitive function in patients with CJD A double-blind study. Neurology. 2004 Mar 9;62(5):714–718. PMID: 15007119
35. Bone I, Belton L, Walker AS, Darbyshire J. Intraventricular pentosan polysulphate in human prion diseases: an observational study in the UK. Eur J Neurol. 2008 May;15(5):458–464. PMID: 18355301

36. Tsuboi Y, Doh-Ura K, Yamada T. Continuous intraventricular infusion of pentosan polysulfate: clinical trial against prion diseases. Neuropathol Off J Jpn Soc Neuropathol. 2009 Oct;29(5):632–636. PMID: 19788637
37. Collinge J, Gorham M, Hudson F, Kennedy A, Keogh G, Pal S, Rossor M, Rudge P, Siddique D, Spyer M, Thomas D, Walker S, Webb T, Wroe S, Darbyshire J. Safety and efficacy of quinacrine in human prion disease (PRION-1 study): a patient-preference trial. Lancet Neurol. 2009 Apr;8(4):334–344. PMCID: PMC2660392
38. Geschwind MD, Kuo AL, Wong KS, Haman A, Devereux G, Raudabaugh BJ, Johnson DY, Torres-Chae CC, Finley R, Garcia P, Thai JN, Cheng HQ, Neuhaus JM, Forner SA, Duncan JL, Possin KL, DeArmond SJ, Prusiner SB, Miller BL. Quinacrine treatment trial for sporadic Creutzfeldt-Jakob disease. Neurology. 2013 Dec 3;81(23):2015–2023. PMCID: PMC4211922
39. Haïk S, Brandel JP, Salomon D, Sazdovitch V, Delasnerie-Lauprêtre N, Laplanche JL, Faucheux BA, Soubrié C, Boher E, Belorgey C, Hauw JJ, Alpérovitch A. Compassionate use of quinacrine in Creutzfeldt-Jakob disease fails to show significant effects. Neurology. 2004 Dec 28;63(12):2413–2415. PMID: 15623716
40. Haïk S, Marcon G, Mallet A, Tettamanti M, Welaratne A, Giaccone G, Azimi S, Pietrini V, Fabreguettes J-R, Imperiale D, Cesaro P, Buffa C, Aucan C, Lucca U, Peckeu L, Suardi S, Tranchant C, Zerr I, Houillier C, Redaelli V, Vespignani H, Campanella A, Sellal F, Krasnianski A, Seilhean D, Heinemann U, Sedel F, Canovi M, Gobbi M, Di Fede G, Laplanche J-L, Pocchiari M, Salmona M, Forloni G, Brandel J-P, Tagliavini F. Doxycycline in Creutzfeldt-Jakob disease: a phase 2, randomised, double-blind, placebo-controlled trial. Lancet Neurol. 2014 Feb;13(2):150–158.
41. Prion Alliance. Prion Alliance sponsors MGH research study [Internet]. 2017 [cited 2018 Mar 7]. Available from: http://www.prionalliance.org/2017/07/19/prion-alliance-sponsors-mgh-research-study/
42. Savage MJ, Kalinina J, Wolfe A, Tugusheva K, Korn R, Cash-Mason T, Maxwell JW, Hatcher NG, Haugabook SJ, Wu G, Howell BJ, Renger JJ, Shughrue PJ, McCampbell A. A Sensitive Aβ Oligomer Assay Discriminates Alzheimer's and Aged Control Cerebrospinal Fluid. J Neurosci. 2014 Feb 19;34(8):2884–2897. PMID: 24553930
43. Giles K, Berry DB, Condello C, Hawley RC, Gallardo-Godoy A, Bryant C, Oehler A, Elepano M, Bhardwaj S, Patel S, Silber BM, Guan S, DeArmond SJ, Renslo AR, Prusiner SB. Different 2-Aminothiazole Therapeutics Produce Distinct Patterns of Scrapie Prion Neuropathology in Mouse Brains. J Pharmacol Exp Ther. 2015 Oct;355(1):2–12. PMCID: PMC4576665
44. Doh-ura K, Ishikawa K, Murakami-Kubo I, Sasaki K, Mohri S, Race R, Iwaki T. Treatment of transmissible spongiform encephalopathy by intraventricular drug infusion in animal models. J Virol. 2004 May;78(10):4999–5006. PMCID: PMC400350
45. Kawasaki Y, Kawagoe K, Chen C, Teruya K, Sakasegawa Y, Doh-ura K. Orally Administered Amyloidophilic Compound Is Effective in Prolonging the Incubation Periods of Animals Cerebrally Infected with Prion Diseases in a Prion Strain-Dependent Manner. J Virol. 2007 Dec;81(23):12889–12898. PMCID: PMC2169081
46. Wagner J, Ryazanov S, Leonov A, Levin J, Shi S, Schmidt F, Prix C, Pan-Montojo F, Bertsch U, Mitteregger-Kretzschmar G, Geissen M, Eiden M, Leidel F, Hirschberger T, Deeg AA, Krauth JJ, Zinth W, Tavan P, Pilger J, Zweckstetter M, Frank T, Bähr M, Weishaupt JH, Uhr M, Urlaub H, Teichmann U, Samwer M, Bötzel K, Groschup M, Kretzschmar H, Griesinger C, Giese A. Anle138b: a novel oligomer modulator for disease-modifying therapy of neurodegenerative diseases such as prion and Parkinson's disease. Acta Neuropathol (Berl). 2013 Jun;125(6):795–813. PMCID: PMC3661926
47. Eric Minikel. Age of onset in genetic prion disease and the design of preventive clinical trials. Prep.
48. Vallabh S. A path to prevention of prion disease. Prep.
49. Takada LT, Kim M-O, Cleveland RW, Wong K, Forner SA, Gala II, Fong JC, Geschwind MD. Genetic prion disease: Experience of a rapidly progressive dementia center in the United States and a review of the literature. Am J Med Genet Part B Neuropsychiatr Genet Off Publ Int Soc Psychiatr Genet. 2017 Jan;174(1):36–69. PMID: 27943639
50. Wilham JM, Orrú CD, Bessen RA, Atarashi R, Sano K, Race B, Meade-White KD, Taubner LM, Timmes A, Caughey B. Rapid End-Point Quantitation of Prion Seeding Activity with Sensitivity Comparable to Bioassays. PLoS Pathog. 2010 Dec 2;6(12):e1001217.

51. Orrù CD, Groveman BR, Hughson AG, Manca M, Raymond LD, Raymond GJ, Campbell KJ, Anson KJ, Kraus A, Caughey B. RT-QuIC Assays for Prion Disease Detection and Diagnostics. Methods Mol Biol Clifton NJ. 2017;1658:185–203. PMID: 28861791
52. Lowry OH, Rosebrough NJ, Farr AL, Randall RJ. Protein Measurement with the Folin Phenol Reagent. J Biol Chem. 1951 Nov 1;193(1):265–275. PMID: 14907713

Evaluation of prion protein quantification in cerebrospinal fluid as a tool for prion disease therapeutic development

Supplementary Materials

Supplementary Discussion

Handling of test-retest samples.

We analyzed test-retest reliability of CSF PrP in four cohorts (Figure S7). Here is what we know about the handling history of these samples:

- Metformin trial placebo controls (Steven Arnold and Aaron Koenig). Mean CV = 13% (Figure 3 and Figure S7A). *N*=18 samples comprise 2 lumbar punctures from each of 9 placebo-treated individuals from a randomized trial of metformin in individuals with mild cognitive impairment due to either Alzheimer disease or suspected non-amyloid pathology (SNAP). Test-retest interval ranges from 8 to 11 weeks. Lumbar punctures were performed fasting between 8:00a and 10:00a. CSF samples were handled according to a uniform protocol by the same staff, aliquotted into 0.5 mL aliquots within 1 hour of collection and then frozen on dry ice before storage at -80°C. The aliquots we received, approximately 1.75 years after the last sample was collected, were all 0.25 mL, indicating another round of freeze/thaw and aliquotting had occurred in the interim, but all samples were received in identical tubes with identical labeling.
- Sapropterin dihydrychloride participants (Kathryn Swoboda). Mean CV = 33% (Figure S7B). *N*=28 samples comprise 3 lumbar punctures from 8 individuals and 2 lumbar punctures from 2 individuals, all with Segawa syndrome (biallelic *GCH1* loss-of-function),enrolled in a trial monitoring effects of sapropterin dihydrochloride or placebo on CSF biomarkers. Test-retest interval ranges from 5 to 25 weeks. Lumbar punctures were performed at various times of day. Details of sample handling history are not known, but the aliquots we received were of various sizes (range: 150 µL to 1.3 mL) and were stored in different types of tubes (screw cap and flip top) with varied labeling (electronically generated and hand-written), suggesting a diverse sample handling history.
- MIND lumbar drains (MGH MIND Tissue Bank). Mean CV = 40% (Figure S7C). *N*=18 samples comprise 3 days of lumbar drains from 4 patients and 2 days of lumbar drains from 3 patients, with a test-retest interval ranging from 1 day to 4 monthsThese individuals were being treated at MGH for normal pressure hydrocephalus (*N*=7), *C. dificile* infection (*N*=1), or *Herpes simplex* infection (*N*=1). These in-patient lumbar drains had contact with diverse plastics for diverse amounts of time before freezing. In general, the samples passed through a pressure-measuring burette made of cellulose acetate propionate (CAP) before draining into a polyvinyl chloride (PVC) bag. CSF was later collected from the bag and frozen in either polystyrene (PS) or polypropylene (PP) tubes. Aliquots we received were of two different sizes: 0.5 mL and 4.0 mL.
- Pre-symptomatic and symptomatic *PRNP* mutation carriers (Michael Geschwind). Mean CV=34% in each (Figure S7D-E). Samples were collected between 2009 and 2017 at two sites (UCSF Parnassus and subsequently UCSF Mission Bay) with multiple different physicians performing lumbar punctures according to a uniform protocol. Test-retest interval ranges from 2 months to 6 years. Samples were collected at various times of day and kept under refrigeration for variable amounts of time (ranging from a few hours to overnight) and then frozen at -80°C until being thawed and aliquotted by UCSF CoreLabs in the first half of 2017. No details are available on the degree of CSF plastic exposure during handling at CoreLabs. Aliquots we received were in identical tubes with uniform labels. All aliquots were labeled as being 250 uL, however, we found that the actual recoverable volume in each tube varied, with some as low as 100 µL; all data reported here are from aliquots with at least 140 µL.

Plate position effects.

To assess whether plate position affects apparent PrP levels in ELISA, we ran two whole ELISA plates loaded with technical replicates of the same CSF sample (v1209 with 0.03% CHAPS). One plate was loaded with a single channel pipette taking 29 minutes (Fig. S2A-B) and the other was loaded with a multichannel pipette taking 11 minutes (Fig. S2C-D). A visually subtle, yet significant (P = 1.5e-14), decline in apparent PrP level is seen across the plate. For instance, in Fig. S2A, the ten replicates loaded last (wells G9-H6) are on average 22% lower than the ten replicates loaded first (wells A11-B8). Adjustment based on the standard curves abolishes this slope, and reduces the CV among technical replicates (Fig S2B and D).

Spike recovery experiments.

While we ultimately achieved 90.5% recovery of recombinant human PrP spiked into CSF, this successful outcome was preceded by a number of experiments that usefully illuminate constraints of working with both the BetaPrion ELISA assay and CSF PrP as an analyte. In our first experiment, recombinant full-length human PrP with concentration orthogonally established by amino acid analysis (AAA) was spiked into two CSF samples previously established to have high and low baseline PrP. Compared to the expected recovery, the recombinant protein gave a much higher signal than expected, with 392-451%, over-recovery (Figure S3A). This surprising finding suggested to us that the concentration of PrP in kit standards may be lower PrP in practice than their stated concentration. To test this hypothesis, we directly compared the kit standard curve to a matched standard curve prepared with our recombinant PrP. This experiment confirming that kit standards appeared lower than AAA-quantified PrP standards by a factor of roughly 4 (Figure S3B). We conclude that kit standards, while technically reproducible, may most usefully inform relative rather than absolute quantification of PrP.

We next attempted to assess spike recovery in an internally consistent system by comparing recombinant PrP spiked into CSF to a recombinant PrP standard curve. We diluted recombinant PrP in CSF, then serially diluted into additional CSF to create a five-point series. The series of samples was re-frozen and measured by ELISA the next day. Under these intensive handling conditions, we observed only ~50% recovery even though the samples contained 0.03% CHAPS (Figure S3C). We hypothesized that the CHAPS additive, while helpful, could not fully protect against the high levels of plastic exposure involved in serial dilution of CSF. To test this hypothesis, we redid the experiment in C with special attention to protecting PrP from plastic adsorption. Recombinant PrP was diluted in blocking to prepare a series of solutions at 100x the desired final concentrations of points in the spike series. These samples were then added to CSF aliquots at a 1:100 concentration, and used in a same-day ELISA experiment. With this level of attention to plastic exposure and the elimination of an additional freeze-thaw cycle relative to the standard curve, PrP was preserved near expected levels with 90.5% recovery observed (Figure S3D).

Finally, to assess recovery from a different angle, we titrated a high-PrP CSF sample into a low-PrP CSF sample at varying ratios, again ensuring minimal and consistent CSF handling. Under these conditions, we observed linear and proportional recovery of PrP (Figure S3E). These experiments provide additional evidence that the quality of PrP measurement afforded by the BetaPrion ELISA assay is dependent on appropriate sample processing.

CSF aliquot size and PrP loss.

We observed that when working with experimental aliquots of CSF, lower volume aliquots appeared to have consistently lower PrP levels (Figure S5A). This effect is likely due to increased exposure of the sample to plastic due to the higher surface area to volume ratio in the polypropylene storage tube. This explanation would be consistent with observed PrP loss across multiple regimens of plastic exposure (see Figure 2). Notably, while aliquot size profoundly impacts PrP recovery from small (< 100 uL) aliquots, it does not appear to impact PrP levels in substantially larger CSF volumes. When comparing 1, 3 and 5 mL draws of a pooled CSF sample into identical 5 mL syringes, we did not see a difference in measured PrP (Figure S5B). The cylindrical shape of the syringe could also contribute to this finding, as the surface-area-to-volume ratio difference between different syringe volumes is less dramatic than that for very small sub-aliquots. These data have clinical implications: while downstream sub-aliquotting and storage can impact PrP levels, different syringe volumes during LPs performed with gentle aspiration will not greatly influence PrP recovery.

Supplementary Table

Collaborator	*N*	Diagnosis	Description
Steven Arnold	18	Alzheimer disease and MCI-SNAP	Placebo-treated controls from a randomized trial monitoring effects of metformin on CSF biomarkers[29]. 8-11 week test-retest. Samples were handled uniformly (see Supplementary Discussion) and were centrifuged prior to freezing.
MGH MIND Tissue Bank	27	NPH, *C. dificile*, herpes simplex	Large volume assay development samples from NPH patients (*N*=9), test-retest lumbar drains (*N*=18), and lumbar-thoracic gradient samples (*N*=8). Samples were centrifuged for 10 minutes at 2,000xG after receipt in our lab.
Kathryn Swoboda	28	Phenylketonuria	Segawa syndrome (*GCH1* loss of function) patients who received either placebo or sapropterin dihydrochloride in a trial monitoring effects on CSF biomarkers. 5-25 week test-retest. Samples were centrifuged for 10 minutes at 2,000xG after receipt in our lab.
Piero Parchi	34	Symptomatic prion and non-prion dementias	Dementia patients referred to the CJD Reference Center at University of Bologna due to suspected prion disease. Samples are autopsy-confirmed positive or negative for prion disease. Prion samples include sporadic and genetic. Prior to arriving at Dr. Parchi's lab from referring physicians, samples were variably centrifuged or not, and variably shipped frozen, cold, or at room temperature. Samples not marked as previously centrifuged were centrifuged for 10 minutes at 2,000xG after receipt in our lab.
Inga Zerr	29	Symptomatic prion and non-prion dementias	Dementia patients referred to the CJD Reference Center at University of Göttingen due to suspected prion disease. Samples are autopsy-confirmed positive or negative for prion disease. Prion samples include sporadic and genetic.

			Samples were centrifuged for 10 minutes at 2,000xG after receipt in our lab. These samples were received after the data in Figure 1 were generated, so we added 0.03% CHAPS prior to sub-aliquotting and ELISA.
Henrik Zetterberg	20	Cognitive impairment	Patients with undiagnosed cognitive impairment and normal levels of CSF tau, phospho-tau, and amyloid beta. Samples were centrifuged for 10 minutes at 2,000xG after receipt in our lab.
Michael Geschwind	61	Symptomatic and pre-symptomatic genetic prion disease	Participants with *PRNP* mutations in the Early Diagnosis of Human Prion Disease study at UCSF[49]. The cohort includes *N*=61 samples from *N*=40 distinct individuals (28 pre-symptomatic and 12 symptomatic), with 1 to 5 samples per person collected at intervals ranging from 2 months to 6 years. Mutations represented include P102L (*N*=4 individuals), D178N (*N*=6), E200K (*N*=16), and ten other mutations (details omitted to protect patient privacy), including five with literature evidence for high penetrance and five without (see companion paper by Minikel et al). These samples were received after the data in Figure 1 were generated, so we added 0.03% CHAPS prior to sub-aliquotting and ELISA. Samples were never centrifuged.
TOTAL	**225**		

Table S1. CSF samples analyzed.

Abbreviations: normal pressure hydrocephalus (NPH); mild cognitive impairment with suspected non-amyloid pathology (MCI-SNAP).

Supplementary Figures

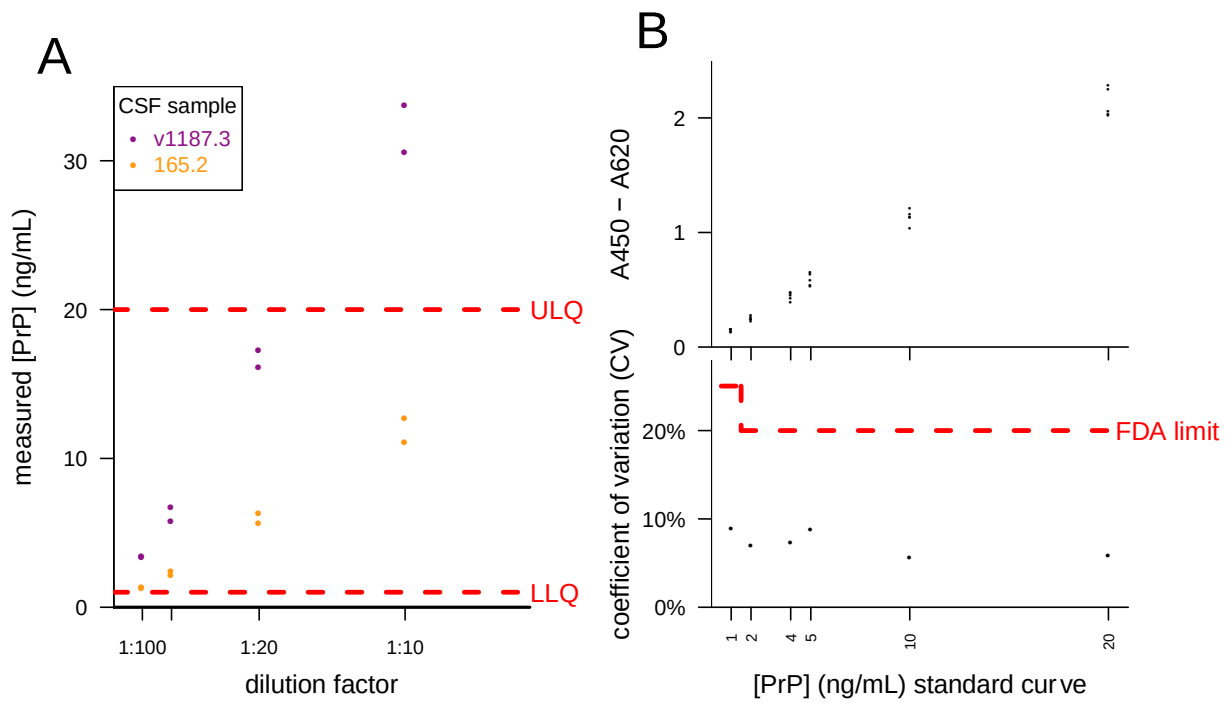

Figure S1. The BetaPrion Human PrP ELISA kit quantifies PrP in a technically reproducible and sensitive manner.

A) Consistent dilution linearity was observed within the assay's stated dynamic range of 1 – 20 ng/mL PrP, providing reassurance that this technique can be used to compare PrP levels across samples even where these levels differ by one log. B) Five replicates of the kit's internal six-point standard curve, reconstituted from lyophilized standards, were run in parallel on one plate. Across the dynamic range of the assay, the coefficient of variation falls below 10% for all points and well below the 20% FDA recommended limit in standard variability for ligand-binding assays.

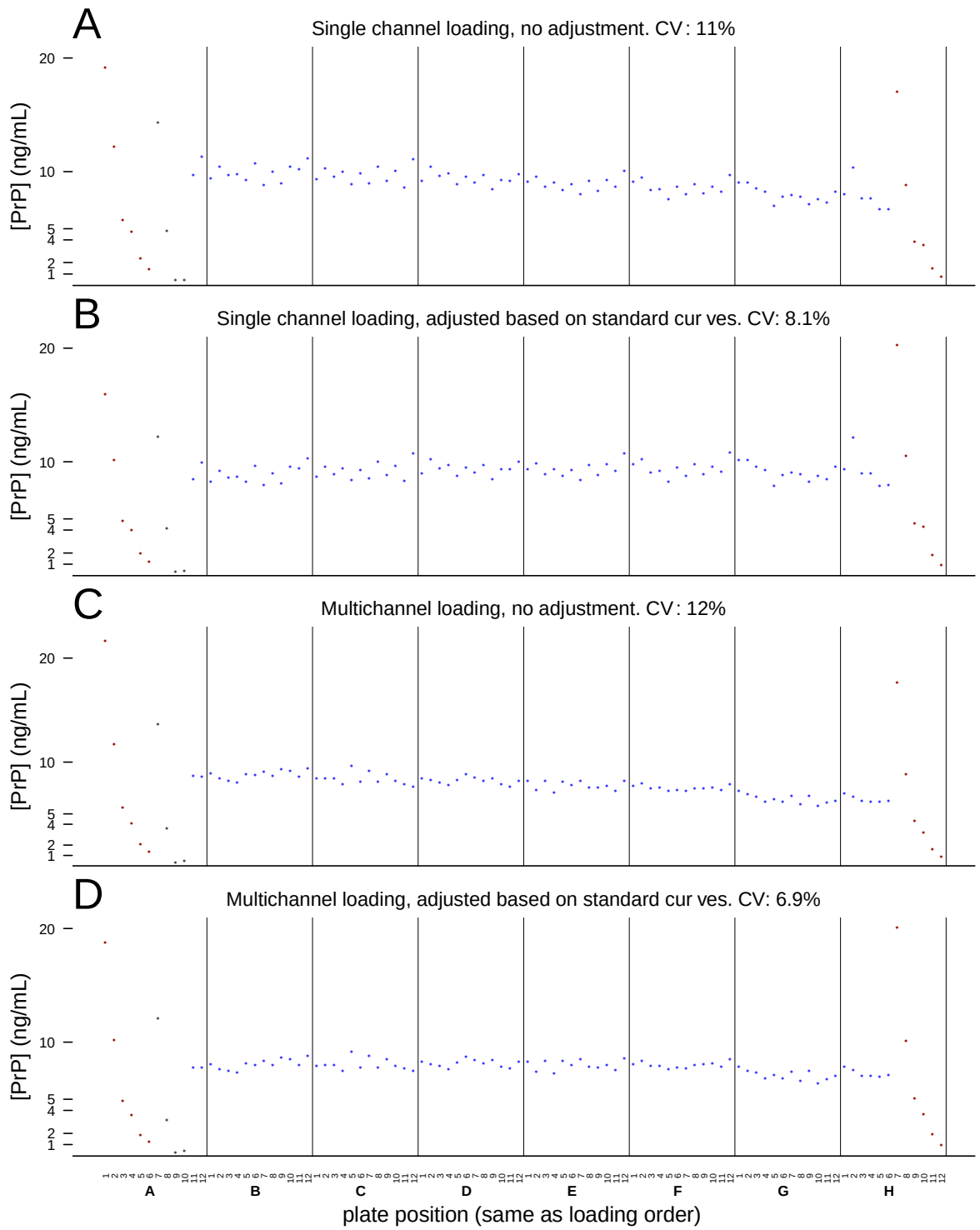

Figure S2. Plate position effects.

Computed PrP levels for standard curves (red), kit controls (gray), or the CSF sample (blue) in two whole plates loaded with technical replicates of the same CSF sample (v1209 with 0.03% CHAPS) using either a single channel pipette (A-B) or a multichannel pipette (C-D). Displayed are the unadjusted PrP values

(A and C) or the PrP values after adjustment based on the difference between the standard curves at the beginning and end of the plate (B and D). See supplementary discussion for further interpretation.

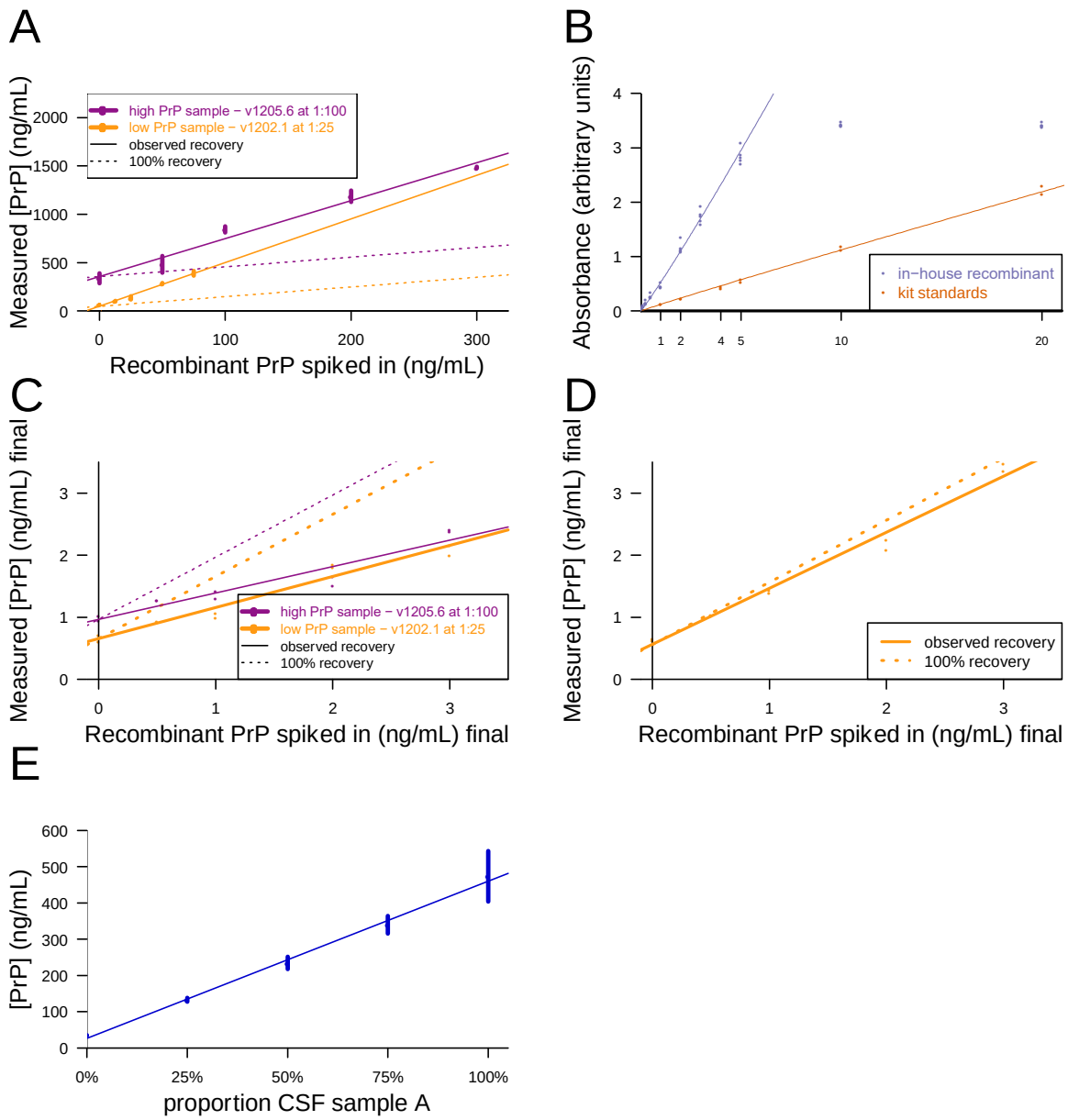

Figure S3. Spike recovery experiments.

A) In-house produced full-length recombinant human prion protein, quantified by amino acid analysis (AAA) was spiked into two CSF samples previously established to have high and low baseline PrP. Recombinant PrP was over-recovered by 392-451% when compared to kit standards. B) A recombinant standard curve was prepared from AAA-quantified recombinant huPrP to match the nominal concentrations of each of the six points on the BetaPrion kit standard curve. Direct comparisons of the two series by ELISA showed the recombinant curve to be contain roughly 4x greater PrP at each point. C) Recombinant huPrP was measured according to a recombinant PrP standard curve. Recombinant PrP was diluted in CSF, then serially diluted into additional CSF to create a five-point series. The series of samples was re-frozen and measured by ELISA the next day. Under these conditions we observed 50.0% and 42.5% recovery for two different samples. D) The experiment in C was redone with the following

modifications. Recombinant PrP was diluted directly in the initial aliquot tube with blocking buffer (5% BSA and 0.05% Tween-20 in PBS, filtered prior to use). It was further diluted in blocking buffer to prepare a series of solutions at 100x the desired final concentrations of points in the spike series. These samples were then added to CSF aliquots at a 1:100 concentration. These samples were then diluted in blocking buffer to their final plating concentration and measured in a same-day ELISA experiment. Under these conditions we observed 90.2% recovery. E) A high-PrP CSF sample (sample A) was titrated into a low-PrP CSF sample at varying ratios, with minimal CSF handling. We observed linear recovery of PrP. See supplementary discussion for further interpretation.

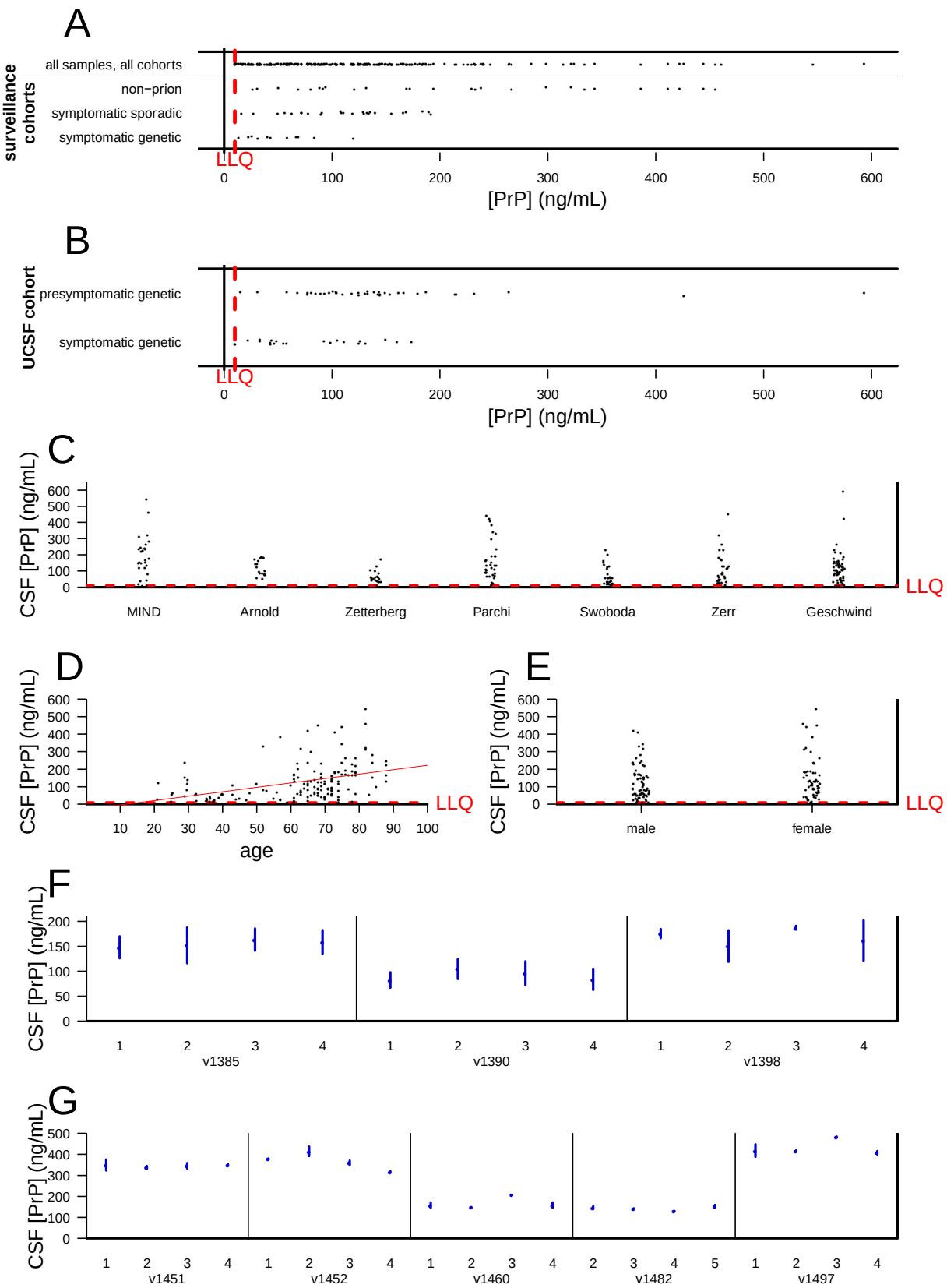
A
surveillance cohorts
all samples, all cohorts
non−prion
symptomatic sporadic
symptomatic genetic
LLQ
0
100
200
300
400
500
600
[PrP] (ng/mL)
B
UCSF cohort
presymptomatic genetic
symptomatic genetic
LLQ
0
100
200
300
400
500
600
[PrP] (ng/mL)
C
CSF [PrP] (ng/mL)
600
500
400
300
200
100
0
LLQ
MIND
Arnold
Zetterberg
Parchi
Swoboda
Zerr
Geschwind
D
CSF [PrP] (ng/mL)
LLQ
10
20
30
40
50
60
70
80
90
100
age
E
CSF [PrP] (ng/mL)
LLQ
male
female
F
CSF [PrP] (ng/mL)
200
150
100
50
0
1
2
3
4
v1385
v1390
v1398
G
CSF [PrP] (ng/mL)
500
400
300
200
100
0
v1451
v1452
v1460
v1482
v1497

Figure S4. Candidate explanations for variability in CSF PrP levels.

A) Within cohorts of individuals referred with a possible diagnosis of prion disease (Zerr and Parchi cohorts), PrP levels are lower in individuals with prion disease than in individuals with other diagnoses. PrP levels in sporadic prion disease CSF average 42% of non-prion samples (P = 0.0001, Kolmogorov-Smirnov test) and in genetic prion disease CSF average 19% of non-prion samples (P = 2.6e-6, Kolmogorov-Smirnov test). B) Among individuals with a PRNP *mutation (Geschwind cohort), PrP levels in symptomatic individuals average 53% of those in pre-symptomatic individuals (P = .001, Kolmogorov-Smirnov test). C) CSF PrP levels vary dramatically between different cohorts in our study (P = 8.0e-6, Type I ANOVA). D) CSF PrP is positively correlated with age (r = 0.47, P = 1.9e-9, Spearman rank test), although among our samples age is confounded with cohort, diagnosis, and likely with other unobserved variables, so it is unclear whether this correlation is biologically meaningful. E) CSF PrP does not differ between men and women (P = 0.31, Kolmogorov-Smirnov test). F) CSF PrP exhibits no lumbar-thoracic gradient within ~30 mL intrathecal CSF drips. From each of three individuals with normal pressure hydrocephalus, 29-32 mL of intrathecal CSF was collected via drip in 4 polystyrene tubes of 7-8 mL each, with "1" being the first tube and "4" being the final tube. Because CSF from further up the spinal column is expected to drain downward as CSF is removed, "1" represents the most lumbar CSF while "4" is the most thoracic. PrP exhibits no trend across tubes (*P *= 0.81, linear regression). G) CSF PrP likewise exhibits no lumbar-thoracic gradient when ~20 mL of CSF is drawn using gentle aspiration with a 24G Sprotte needle. Approximately 5 mL of CSF was drawn in each of four syringes; again, "1" is the most lumbar and "4" is the most thoracic. These samples included individuals diagnosed with Alzheimer's disease, Parkinson's disease, and undiagnosed individuals. PrP exhibits no trend across syringes (*P *= 0.93, linear regression).*

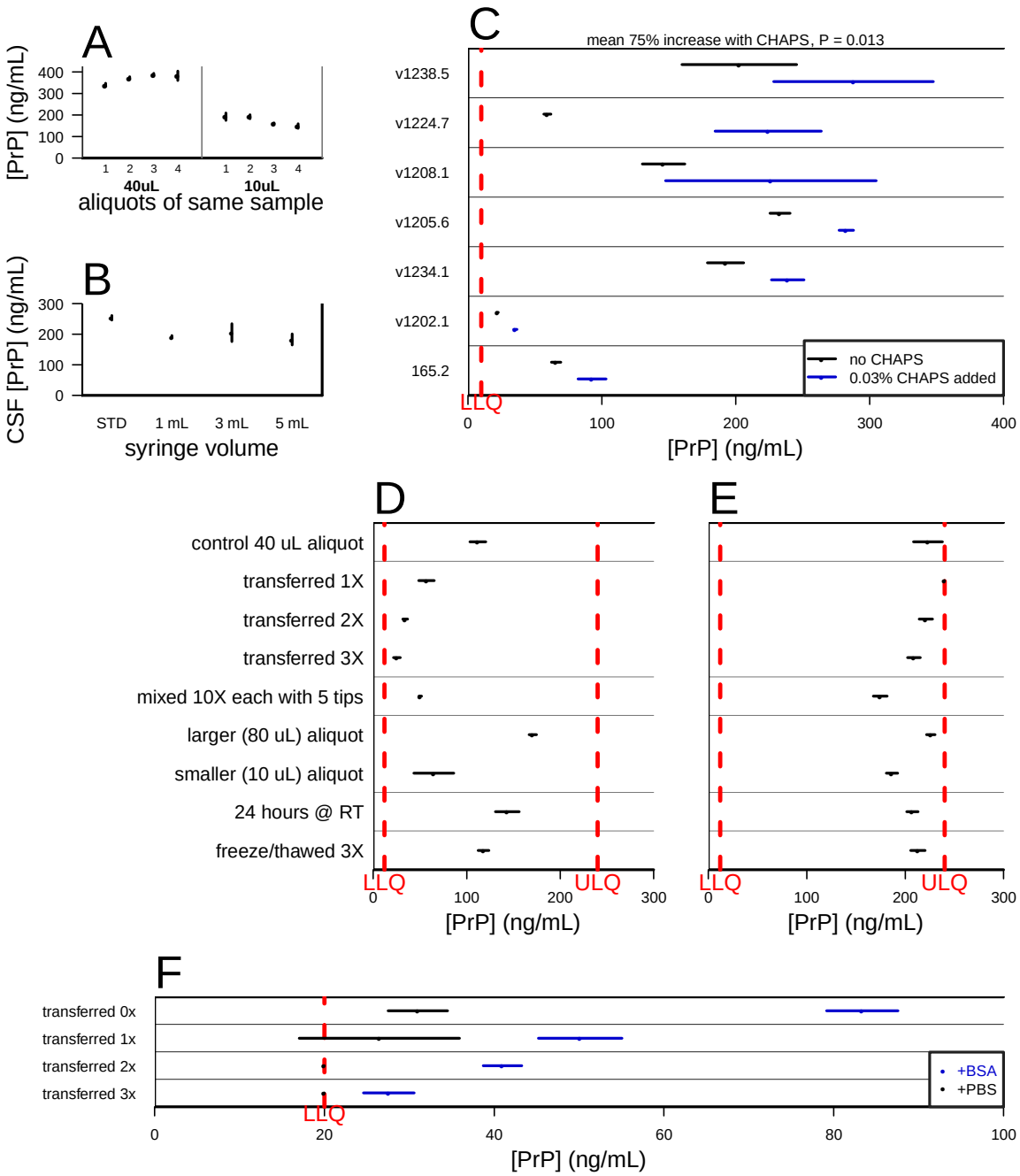

Figure S5. Additional evidence for loss of PrP to plastic adsorption.

A) Differently sized aliquots of sample v1187 appear to have different PrP levels. Each dot is the mean, and line segment the 95% CI, of two technical replicates on the same plate. These samples did not contain CHAPS. B) A pooled CSF standard (STD) was warmed to 37°C and various volumes (1 mL, 3 mL, or 5 mL) were drawn into identical 5 mL syringes using a 24G Sprotte needle and allowed to sit for 15 minutes before ejection into tubes, centrifugation, and aliquotting. Samples were handled identically

except for the volume drawn into the syringe. See supplementary discussion. C) After aliquotting and freeze/thaw, CSF samples were diluted into blocking buffer neat (black) or after addition of 0.03% CHAPS (final concentration) to the original storage tube. Addition of CHAPS resulted in a 75% increase in apparent PrP level. See supplementary discussion. D and E) Replication of the findings from Figure 1A-B. The data in Figure 1 were generated using CSF samples from two different individuals; to rule out the possibility that some other inter-individual difference, rather than CHAPS, explained the difference in plastic loss, we repeated the experiment but with a single CSF sample divided into two halves which were then aliquotted without (D) or with (E) 0.03% CHAPS, subjected to the same battery of perturbations and plated at the same dilution. Because CHAPS increases overall PrP recovery, some replicates in (E) are at the upper limit of quantification; nevertheless, the results recapitulate Figure 1. F) 1 mg/mL (final concentration) BSA, or PBS as a control, were added to CSF sample 165.2, which had an initial total protein level at the low end of the distribution of our samples (measured at 0.22 mg/mL with PBS), bringing it up to a total protein level at the high end of our samples (measured at 1.15 mg/mL after BSA spike-in). BSA or PBS were added after centrifugation but prior to aliquotting at 40 uL and re-freezing. 4 tubes of each sample were subsequently thawed and diluted into blocking buffer for analysis. Total recovery of PrP is increased in the BSA-spiked samples, analogous to panel B, although BSA is less effective at mitigating loss upon further transfer between tubes (compare to Figure 2A).

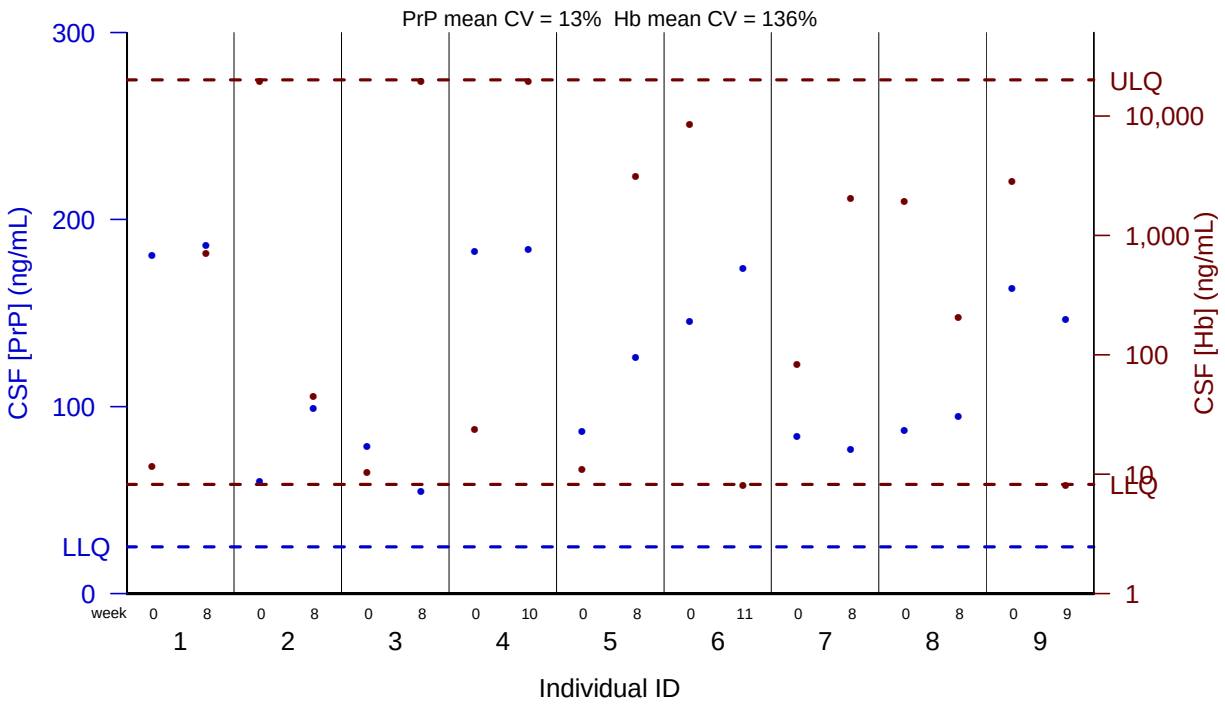

Figure S6. Hemoglobin in test-retest samples.

Overlaid are PrP levels (blue, same data as shown in Figure 3) and hemoglobin levels (red) in test-retest samples. PrP exhibited good test-retest reliability (CV=13%) despite dramatic variation in hemoglobin (CV=136%), providing further evidence that blood contamination does not influence CSF PrP level.

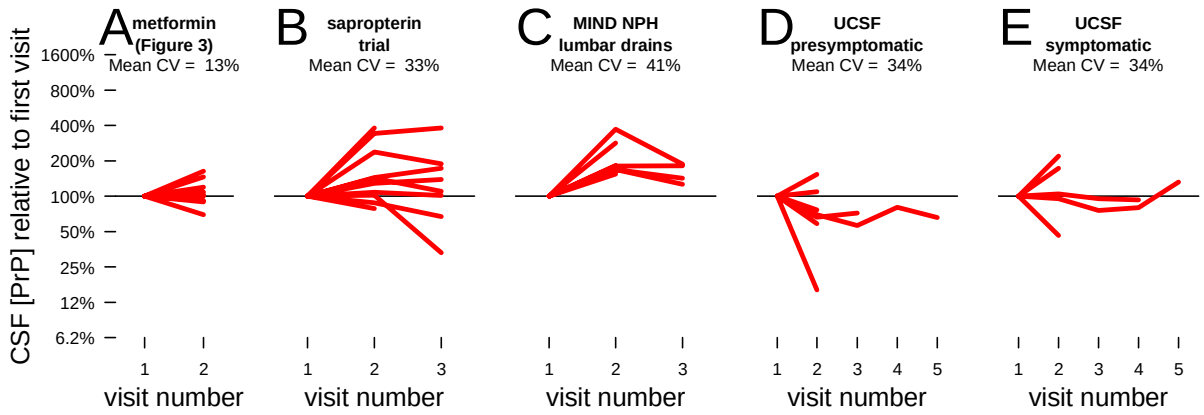

Figure S7. Test-retest reliability of CSF PrP in additional cohorts.

Test-retest CSF PrP levels in A) metformin trial participants (Arnold) over 8-11 weeks, with mean CV=13% (same data from Figure 3 but plotted normalized to the PrP level at the first visit); B) sapropterin dihydrochloride trial participants (Swoboda) over 5-25 weeks, with mean CV=33%, C) NPH lumbar drains (MGH MIND Tissue Bank) over 1 day to 4 months, with mean CV=40%, D) pre-symptomatic and E) symptomatic PRNP *mutation carriers (Geschwind) over 2 months to 6 years, each with mean CV=34%. The repeated 34% is not an error: the mean CVs in (D) and (E) happen to be the same (34.28% and 34.25%). See supplementary discussion for details on sample handling in these cohorts.*

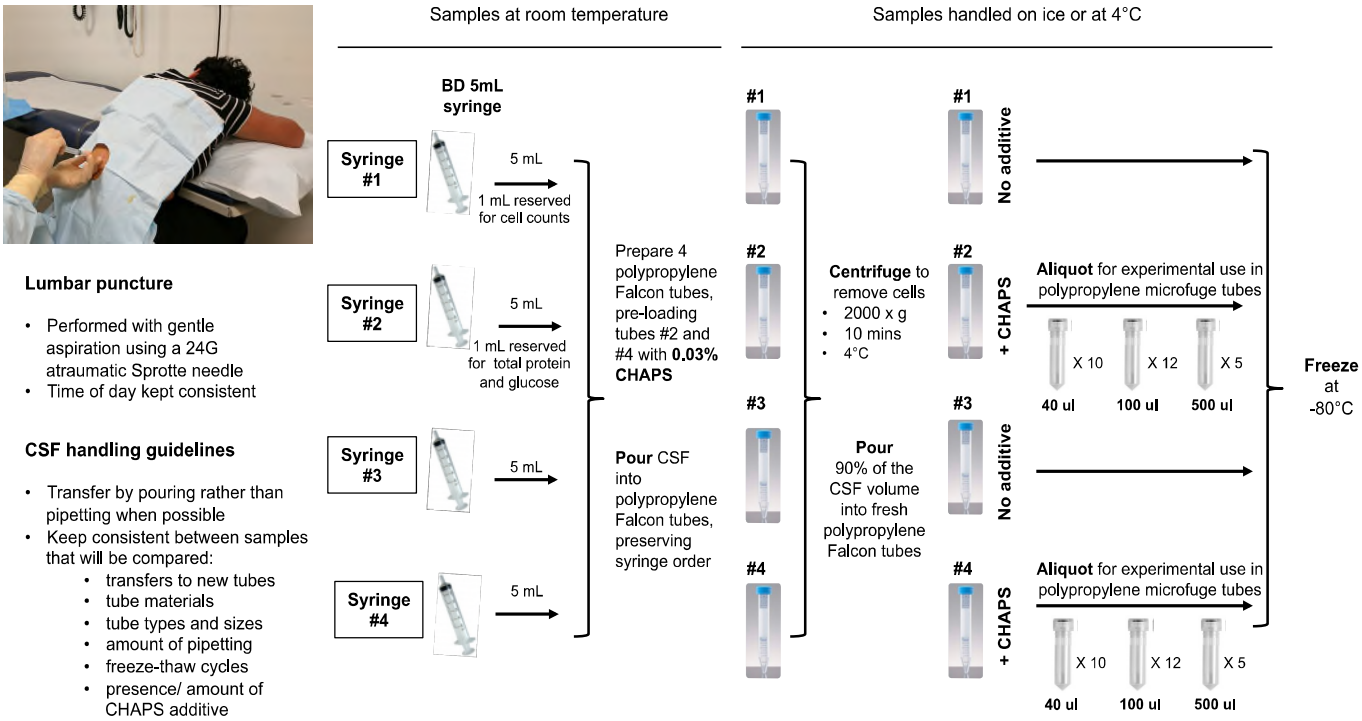

Figure S8. Protocol for collection of CSF for PrP measurement.

We have incorporated our findings into the above protocol, which we are using to collect test-retest CSF for the purposes of PrP measurement in our ongoing clinical study.