Bacterial infections represent a rapidly growing challenge to human health. Aminoglycosides are widely used broad-spectrum antibiotics, but they inflict permanent hearing loss in up to ~50% of patients by causing selective sensory hair cell loss. Here, we hypothesized that reducing aminoglycoside entry into hair cells via mechanotransducer channels would reduce ototoxicity, and therefore we synthesized 9 aminoglycosides with modifications based on biophysical properties of the hair cell mechanotransducer channel and interactions between aminoglycosides and the bacterial ribosome. Compared with the parent aminoglycoside sisomicin, all 9 derivatives displayed no or reduced ototoxicity, with the lead compound N1MS 17 times less ototoxic and with reduced penetration of hair cell mechanotransducer channels in rat cochlear cultures. Both N1MS and sisomicin suppressed growth of *E. coli* and *K. pneumoniae*, with N1MS exhibiting superior activity against extended spectrum β-lactamase producers, despite diminished activity against *P. aeruginosa* and *S. aureus*. Moreover, systemic sisomicin treatment of mice resulted in 75% to 85% hair cell loss and profound hearing loss, whereas N1MS treatment preserved both hair cells and hearing. Finally, in mice with *E. coli*-infected bladders, systemic N1MS treatment eliminated bacteria from urinary tract tissues and serially collected urine samples, without compromising auditory and kidney functions. Together, our findings establish N1MS as a nonototoxic aminoglycoside and support targeted modification as a promising approach to generating nonototoxic antibiotics.
Designer aminoglycosides prevent cochlear hair cell loss and hearing loss

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Bacterial infections represent a rapidly growing challenge to human health. Aminoglycosides are widely used broad-spectrum antibiotics, but they inflict permanent hearing loss in up to ~50% of patients by causing selective sensory hair cell loss. Here, we hypothesized that reducing aminoglycoside entry into hair cells via mechanotransducer channels would reduce ototoxicity, and therefore we synthesized 9 aminoglycosides with modifications based on biophysical properties of the hair cell mechanotransducer channel and interactions between aminoglycosides and the bacterial ribosome. Compared with the parent aminoglycoside sisomicin, all 9 derivatives displayed no or reduced ototoxicity, with the lead compound N1MS 17 times less ototoxic and with reduced penetration of hair cell mechanotransducer channels in rat cochlear cultures. Both N1MS and sisomicin suppressed growth of E. coli and K. pneumoniae, with N1MS exhibiting superior activity against extended spectrum β lactamase producers, despite diminished activity against P. aeruginosa and S. aureus. Moreover, systemic sisomicin treatment of mice resulted in 75% to 85% hair cell loss and profound hearing loss, whereas N1MS treatment preserved both hair cells and hearing. Finally, in mice with E. coli–infected bladders, systemic N1MS treatment eliminated bacteria from urinary tract tissues and serially collected urine samples, without compromising auditory and kidney functions. Together, our findings establish N1MS as a nonototoxic aminoglycoside and support targeted modification as a promising approach to generating nonototoxic antibiotics.

Introduction

Bacterial infections commonly overwhelm host defenses and require antimicrobial therapy. For over twenty years and despite newer alternative antibiotics, aminoglycosides remain the mainstay treatment worldwide for numerous disease entities, including pneumonia, peritonitis, sepsis, and genitourinary tract infection (1, 2). The salient features of aminoglycosides include potent antimicrobial activities and minimal drug-related allergies. On the other hand, their major limiting side effects are nephrotoxicity, loss of vestibular function, and permanent hearing impairment, which is detected in approximately 20% of treated patients using conventional audiometry (3, 4). When higher frequency hearing is examined, hearing loss is found in almost half of treated patients (47%) (5). This prevalence may be even higher at longer periods after treatment when considering the prolonged half-life of drug in the inner ear cochlea and the irreversible nature of cochlear hair cell loss (6). Despite these side effects, the World Health Organization recommends aminoglycosides as critically important antimicrobials for clinical use (7). At present, aminoglycoside-induced hearing loss represents one of the most common iatrogenic and preventable forms of hearing loss.

Conflict of interest: A patent application on the synthesis of novel aminoglycoside has been filed (application no. 14/212,964; Alan G. Cheng, Robert Greenhouse, Anthony J. Ricci). Submitted: July 21, 2014; Accepted: November 13, 2014.

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Results

Novel aminoglycoside derivatives exhibit decreased ototoxicity in vitro.

Electrochemical gradients drive cations (calcium and aminoglycosides) (24). Although the molecular nature of this channel remains controversial, a significant body of literature exists on the biophysical properties (24, 26–30). Given that aminoglycosides are permeable blockers of the MET channel, we hypothesized that targeted modification to reduce positively charged sites on the aminoglycoside molecule would hinder drug entry into hair cells and thus prevent ototoxicity (9). Using established synthetic methods (31), we first chemically protected 3 of the amine groups on the aminoglycoside sisomicin, a biosynthetic precursor of gentamicin, thus allowing subsequent modification of the N1 and/or N3′′ amine site (Supplemental Figure 1, A and B; supplemental material available online with this article; doi:10.1172/JCI77424DS1). Sisomicin was selected because it is a hair cell MET channel is required for drug toxicity (9, 20–23), we have redesigned and modified the aminoglycoside sisomicin based on the biophysical properties of the hair cell MET channels (24) and aminoglycoside-bacterial ribosome interactions (25). Here, we have characterized 9 sisomicin derivatives with diminished ototoxicity in vitro, with 3 of the 9 compounds exhibiting comparable anti–E. coli activities to the parent compound sisomicin. The lead compound, N1MS, showed reduced permeation of the MET channel, likely due to the reduced charge per molecule of N1MS. In a mouse model of aminoglycosine-induced deafness, N1MS was significantly less ototoxic than sisomicin. Finally, N1MS treatment eliminated urinary tract infection in vivo. Collectively, our study characterizes a novel nonototoxic aminoglycoside and also introduces an approach to modifying existing aminoglycosides that can reduce ototoxicity while retaining antimicrobial activity.
commercially available at high purity (>98%) as compared with gentamicin. We selected 3 moieties (methylsulfonfyl [MS], phenylsulfonfyl [PS], and benzoyl [BZ]) to modify these 2 amine groups (1 and 3′) (Figure 1B and Supplemental Figure 1B), which were predicted by X-ray crystallography as dispensable sites for the bacterial ribosome binding-dependent antimicrobial effects of aminoglycosides (25). These functional groups were conjugated to the 1 amine group (N1MS, N1PS, N1BZ), 3′ amine group (N3′MS, N3′PS, N3′BZ), or both the 1 and 3′ amine groups (N1,3′MS, N1,3′PS, N1,3′BZ) of sisomicin (Figure 1B, Supplemental Figure 1C, and Supplemental Figure 2). The chemical synthetic schemes are detailed in Supplemental Figure 1 and ref. 32.

Like gentamicin, sisomicin (200 μM for 1 hour) caused a basal-apical gradient of hair cell loss in rat cochlear cultures (Figure 1, C–H, and Supplemental Table 1). At the molar equivalent of the parent compound sisomicin (200 μM), all 9 new sisomicin derivatives induced markedly less hair cell loss, with 4 compounds showing almost no hair cell toxicity (Figure 1G and Supplemental Table 1). Conjugation with the MS moiety was more effective than that with either the PS or BZ structures in ameliorating ototoxicity (Supplemental Figure 3, A–C), and all 3 modifications of the sisomicin backbone with the MS moiety eliminated ototoxicity (Supplemental Figure 3, D–F). Dose-response experiments (drug exposure for 1 hour, as above) showed that N1MS (>95% pure, Supplemental Figure 2) is 17 times less toxic than sisomicin (98% pure, $K_D = 100 \pm 2 \mu M$ and 1.7 ± 0.2 mM, respectively; Figure 1H and Supplemental Table 2). These data suggest that specific modification of aminoglycosides effectively reduced toxicity against hair cells in vitro.

**Novel aminoglycoside derivatives show antibacterial activities in vitro.** Enterobacteriaceae rank among the most frequently isolated organisms from patients (33). Based on this, we next tested the antimicrobial activities of sisomicin and its derivatives against *E. coli* in vitro. Sisomicin and 2 sisomicin derivatives (N1MS and N1PS) showed comparable minimal inhibitory and bactericidal concentrations (using a concentration of <4 μg/ml to define antimicrobial activity; ref. 34 and Figure 2). All 6 compounds modified at the 3′ amine site showed diminished antimicrobial effects (N3′MS, N3′PS, N3′BZ, N1,3′MS, N1,3′PS, N1,3′BZ; Figure 2).

Because N1MS displayed the most favorable antibacterial activity-ototoxicity profile, it was further tested against clinical isolates of *E. coli* (9 of 10), including all 3 extended spectrum β-lactamase-producing (ESBL-producing) strains (Figure 3A), which are multidrug resistant and known to be associated with high rates of patient mortality (35, 36). N1MS inhibited 8 of 10 *K. pneumoniae* strains (including 3 of 5 ESBL producers), whereas sisomicin was active against 6 of 10 strains (1 of 5 ESBL producers; Figure 3B). Compared with sisomicin, N1MS showed diminished activities against *P. aeruginosa* and *S. aureus* strains ($P < 0.05$ for both; Figure 3, C and D). While modifying the 3′ amine group abolished antibacterial activities of all 6 sisomicin derivatives (Figure 2), 3 of 6 (N3′PS, N1,3′PS, N1,3′BZ) compounds retained some ototoxic effects (Supplemental Figure 3). Conversely, modifying the 1 amine alone reduced the spectrum of antibacterial effects; enhanced activity against *E. coli* and *K. pneumoniae*, consistent with previous results on the aminoglycoside apramycin (16). However, the findings that N1MS showed decreased toxicity against hair cells (17 times less ototoxic), *P. aeruginosa* species (22 times less ototoxic), and *S. aureus* species (18 times less ototoxic) suggest that such dissociation may be species specific. Whether loss of antibacterial activity results from decreased entry into bacteria (2) and/or diminished interaction with bacterial ribosomes remains to be determined.

**Novel aminoglycoside shows diminished entry via hair cell MET channels.** Aminoglycosides are permeant blockers of the hair cell MET channels (10, 24, 27). To assess aminoglycoside trafficking across MET channels, electrophysiological measurements of rat cochlear hair cells were performed in vitro. As expected, sisomicin (100 μM) reduced inward currents elicited by mechanical stimulation (Figure 4A). In comparison, current amplitudes in the presence of an identical concentration of N1MS were larger, indicating that N1MS acted as a lower affinity blocker for the MET channels than sisomicin.

Furthermore, voltage clamping of hair cells showed decreased inward and outward currents in the presence of sisomicin or N1MS across all voltages tested (Figure 4, A and B). The nonlinear voltage-current relationships after drug treatment (sisomicin or N1MS) suggest that both drugs acted as permeant blockers, whose ability to reduce MET channel currents (and thus block the channel) was diminished at the most negative and positive holding potentials. Dose-response experiments at a holding potential of ~80 mV...
showed that drug concentrations blocking 50% of MET channel currents were lower for sisomicin than N1MS (K_D = 65.0 ± 17.7 and 96.1 ± 9.9 μM, respectively) (Figure 4C). Likewise, at the other negative holding potentials examined, the K_D for sisomicin was significantly lower than that for N1MS (P < 0.0001, 1-way analysis of covariance; Figure 4D). Taken together and considering that N1MS is less positively charged than sisomicin, these data indicate that N1MS is less likely to traverse the hair cell MET channel and thus enter hair cells than the parent compound sisomicin.

**Novel aminoglycosides prevent hair cell loss and hearing loss in vivo.**

To compare the ototoxicity of sisomicin and N1MS in vivo, we tested them in a deafness paradigm in mice (37). By challenging 30-day-old normal hearing CBA/CaJ mice with a combination of sisomicin and a loop diuretic (single injection of 175 mg/kg sisomicin followed by 300 mg/kg furosemide; Figure 5A), we induced substantially elevated thresholds in auditory brainstem responses (ABRs) and distortion product otoacoustic emissions (DPOAEs) 1 and 5-6 weeks later (Figure 5, C, E, and F). In contrast, we detected no significant threshold shifts in ABR and DPOAE measurements, except a shift from 8 to 17 dB at the 2 highest frequencies, 1 and 5-6 weeks after N1MS treatment (Figure 5, D-F).

Surface preparation of cochleae from sisomicin-treated mice displayed extensive outer hair cell loss in the middle and basal turns (16.9% ± 10.1% and 11.1% ± 10.5% of saline-treated controls, P < 0.001 for both; n = 9 mice; Figure 6, A and B, and Supplemental Table 3), corresponding to loss of auditory function in those animals. Conversely, cochleae from N1MS-treated animals showed substantially more hair cells than sisomicin-treated animals, and thus less toxicity, 1 week and 5-6 weeks after treatment (Supplemental Table 3), consistent with their auditory measurements, which were comparable to those of saline-injected animals (Figure 5, E and F).

To rule out collateral toxicity by sisomicin and N1MS outside the auditory system, 35 different types of organs were examined 3 days after drug administration. Among 5 sisomicin-treated animals, acute renal tubular epithelial degeneration was detected in 2 animals, whereas no tissue toxicity was detected in any of the 10 N1MS-treated animals (Supplemental Table 4). Moreover, we performed dose-response experiments in vivo to determine drug doses that induced animal death and found that sisomicin was lethal at lower doses than N1MS (LD_50: 200 ± 2 mg/kg and 544 ± 7 mg/kg, respectively; Supplemental Figure 4). Based on this, we tested the effects of a higher sub-lethal dose of N1MS and combined it with loop diuretic challenge (400 mg/kg N1MS and 300 mg/kg furosemide). While sisomicin caused ~100% animal mortality at this dose, >95% N1MS-treated animals survived for over a month under these conditions. After treatment with N1MS at this higher dose, there were marked ABR and DPOAE threshold shifts with cor-
25-g animal) effectively suppressed bacteriuria (Figure 7, B–D). Moreover, bladder and kidney homogenates collected on day 6 demonstrated that both sisomicin and N1MS reduced bacterial titers in urinary tract issues (Figure 7, E and F). One week after treatment, N1MS- and sisomicin-treated mice exhibited normal ABR and DPOAE waveforms and thresholds and also normal serum creatinine levels (625 μg for both; Supplemental Figure 5). In summary, these results indicate that N1MS is effective at eliminating E. coli–mediated urinary tract infection, without compromising auditory and kidney functions.

Discussion
Aminoglycosides are potent antibiotics that are actively used worldwide, with ototoxicity being the major dose-limiting side effect. Our study uses a novel chemical synthetic approach for alleviating aminoglycoside ototoxicity while preserving anti-

Figure 4. Hair cell MET responses at different membrane holding potentials after sisomicin and N1MS treatment. (A and B) Mechanical stimulation (a negative step of 650 nm for 0.1 ms, then a positive step of 650 nm for 5 ms) was used to stimulate hair cell hair bundles at different membrane holding potentials (stepped from -180 to +120 in 20-mV increments). Responses to mechanical stimuli were obtained at different holding potentials to generate the current responses shown in the absence and presence of sisomicin (red) or N1MS (blue, both at 100 μM). Sisomicin reduced current amplitudes more effectively than N1MS and thus acts as a higher affinity blocker for the MET channel. Current-voltage plots show that sisomicin reduced both inward (at negative potentials) and outward currents (at positive potentials) and displayed loss of block at both extreme negative and positive steps, indicating that sisomicin acts as a permeant blocker of the MET channel. Measurements under identical conditions found that blockage with N1MS was markedly diminished. (C) Remaining fraction of control current for sisomicin and N1MS at a holding potential of -120 mV at different concentrations (10, 30, 100, 300, and 1,000 μM). (D) Kₐ derived from remaining control current fraction for sisomicin and N1MS at different holding potentials and concentrations (-180 to +120, 20-mV increments). Data are shown as average ± SD. n = 2–9.
We modified the aminoglycoside compound based on the notion that hindering aminoglycoside entry via hair cell MET channel prevents ototoxicity (9, 20). The design was based on the biophysical properties of the MET channel (24, 26), whose candidate molecular compositions are still being elucidated (22, 40–42). Nonetheless, electrochemical gradients drive cations through the MET channel; therefore, the conversion of basic amine sites of aminoglycosides into carboxamides or sulfonamides renders them nonbasic (less positively charged) and was predicted to decrease drug entry and subsequent toxicity. Our paradigm produced sisomicin derivatives exhibiting diminished in vitro toxicity relative to the parent compound sisomicin, with the lead compound N1MS less capable of crossing the MET channels than sisomicin. While the electrophysiological measurements were made in vitro to assess drug entry across the MET channel, the electrochemical gradient present in vivo in the intact cochlea is substantially larger. This difference may in part account for the 17-fold decreased ototoxicity in vivo and 2.3-fold decreased ototoxicity in vivo between N1MS and sisomicin. As the MET channel pore size is estimated at 1.25 ± 0.08 nm at its narrowest segment (24), it is possible that the larger sizes of sisomicin derivatives may have also impeded drug entry. However, the effects of compound dimension are likely limited, as the moieties added were relatively small. Thus, future experiments using bulkier moieties may further delineate the relationships among aminoglycoside dimensions and drug entry and ototoxicity.

A rich body of literature supports the hypothesis that oxidative stress mediates aminoglycoside-induced hair cell degeneration (12, 43), yet the initial events that generate reactive oxygen species are poorly understood. Building upon the knowledge that the human mitochondrial mutation A1555G (GenBank accession no. NC 012920) increases the risk of hearing loss after aminoglycoside treatment (44), recent work has revealed the potential roles of mitochondrial stress in aminoglycoside ototoxicity (16, 45). In particular, work on apramycin, a structurally unique aminoglycoside used in veterinary medicine, suggests that its differential antiribosomal activities against eukaryotic cells versus bacteria contribute to its low ototoxic potential. Moreover, recent work suggests that aminoglycosides induce hair cell toxicity by causing ribotoxic stress and inhibit protein synthesis (46). While our data support the conclusion that decreased drug entry via MET channels underlies diminished aminoglycoside ototoxicity, we did not determine whether sisomicin and sisomicin derivatives differentially bind eukaryotic and bacterial ribosomes, induce ribotoxic stress, or inhibit protein synthesis in hair cells. One or all of these mechanisms may have also contributed to N1MS’s decreased ototoxicity.

Because aminoglycosides can provide broad coverage of gram-negative organisms, they are widely used when the offending organisms are unknown, such as in the setting of neonatal sepsis or peritonitis (47, 48). Additionally, aminoglycosides are clinically indicated for treating pneumonia caused by *P. aeruginosa* and urinary tract infection caused by *E. coli* (2). Differential binding affinities for...
bacterial ribosomes may contribute to the selectivity of individual aminoglycosides (49, 50). The findings that modification at the 3′ amine site reduced antibacterial activity and that N1MS is selectively active against E. coli and K. pneumoniae are consistent with such a structure-activity relationship. Although N1MS shows decreased activity against P. aeruginosa and S. aureus, it is conceivable that a higher dose of the less ototoxic N1MS may be used to overcome its diminished antimicrobial activity against these organisms. The effects on nephrotoxicity of such a regimen will need to be elucidated. Alternatively, modifications at the 1 amine site may further separate ototoxicity from antimicrobial activity and restore efficacy against these organisms. The structural assignments were also confirmed using a Thermo Ultimate 3000 RSLHPLC system.

Electrophysiology. P7–9 rat cochlear explants were prepared and whole cell patch recordings were obtained from inner hair cells as previously described (19, 53). The pipette solution contained 125 mM CsCl, 3.5 mM MgCl₂, 5 mM ATP, 5 mM creatine phosphate, 10 mM HEPES, 1 mM EGTA, 2 mM ascorbate (pH = 7.2), 280–285 mOsm per kg water, while the extracellular solution contained 140 mM NaCl, 2 mM KCl, 2 mM CaCl₂, 2 mM MgCl₂, 10 mM HEPES, 6 mM glucose, 2 mM pyruvate, 2 mM ascorbate (pH = 7.4), 300–310 mOsm per kg water. A glass probe affixed to a piezoelectric stack was used to mechanically stimulate the hair bundles; stimulus amplitudes were selected to provide the maximal positive and negative response.

Immunohistochemistry. As previously described (9), cultured tissues were fixed with 4% paraformaldehyde in PBS at pH 7.4 for 20 minutes at room temperature. For adult cochlear tissues, fixative was gently infused through an apical bony window and the oval window and then incubated in fixative for 45 minutes at room temperature. EDTA was applied to tissues (500 mM for 30 to 40 minutes), before washing with PBS 3 times. Bony capsules of cochleae were microdissected away, and stria vascularis and tectorial membranes were removed to expose the organ of Corti.

Tissues were then immersed in a blocking solution containing 5% bovine serum albumin and Triton-X 1% in PBS for 1 hour. Samples were incubated with anti-myosin VIIa antibody (1:1,000; Proteus Biosci-
To determine the minimum bactericidal concentration (MBC) of the aminoglycoside compounds, we streaked out 50 μl from aminoglycoside-containing, bacteria-inoculated tubes that exhibited no bacterial growth during MIC assays onto Müller-Hinton agar (Becton Dickinson) and incubated them overnight at 37°C. Lack of bacterial growth was used to confirm the MBC for each aminoglycoside compound.

For testing against other bacterial strains, sisomicin and derivatives were sent to the Clinical Microbiology Institute, where MIC’s were determined using the above methods.

Mouse model of urinary tract infection. Procedures were performed as previously described (39). Briefly, type I pili expression was induced in the uropathogenic *E. coli* strain UTI89 by inoculating bacteria into the bladders of female 7- to 8-week-old CBA/CaJ mice by transurethral catheterization. For drug treatment, infected mice were injected subcutaneously with sisomicin or N1MS (25–625 μg) dissolved in 100 μl of PBS) every 2 hours for a total of 5 injections after UTI89 infection.

Aseptically excised bladders and kidneys were minced and homogenized in 400 μl sterile PBS. Freshly collected urine or tissue homogenates were then serially diluted 10- to 1,000-fold. Twenty-five μl of each dilution was plated onto MacConkey agar plates. CFUs were counted after incubation at 37°C overnight. The following day, tissues were incubated with 106 CFU bacteria. Serial 2-fold dilutions of the aminoglycoside compounds, we streaked out 50 μl from aminoglycoside-containing, bacteria-inoculated tubes that exhibited no bacterial growth during MIC assays onto Müller-Hinton agar (Becton Dickinson) and incubated them overnight at 37°C. Lack of bacterial growth was used to confirm the MBC for each aminoglycoside compound.

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overnight incubation at 37°C. The limits of detection were 4,000 CFU/ml for urine and 160 CFU per bladder. To determine creatinine levels, 25 μL of serum was collected from each mouse and sent to the Diagnostic Laboratory of Veterinary Service Center at Stanford University.

**Auditory measurements.** ABRs and DPOAEs were measured as previously described with custom hardware based around a data acquisition board (PCOe-6251, National Instruments) driven by software written in MATLAB (Mathworks) (55, 56). Briefly, mice were sedated with a mixture of ketamine (100 mg/kg) and xylazine (10 mg/kg). ABR signals were measured from a needle electrode positioned inferior to the tympanic bulla, referenced to an electrode placed at the vertex of the head, and a ground electrode was placed at the hind leg. Tone burst stimuli were delivered with frequencies ranging from 4 to 64 kHz (4, 8, 16, 32, 64 kHz) and sound intensities raised from 10 to 80 dB sound pressure level (SPL) in 10-dB steps. At each frequency and sound level, 260 trials were sampled and averaged.

DPOAEs were measured by a probe tip microphone in the external auditory canal. The sound stimuli were two 1-second sine wave tones of differing frequencies (F2 = 1.22 × F1). F2 was varied from 4 to 46 kHz, and the intensities of 2 tones were from 20 to 80 dB SPL with 10-dB steps. The amplitude of the cubic distortion product was measured at 2 × F1–F2. The threshold at each frequency was calculated to be when the DPOAE was >5 dB SPL and 2 SDs above the noise level. For statistical analyses of both ABR and DPOAE responses, a lack of response is designated 80 dB SPL.

**Histology of organs (necropsy).** All procedures were performed by a board-certified veterinary pathologist at the Diagnostic Laboratory of Veterinary Service Center at Stanford University. First, a complete gross examination of organs and tissues was performed. A comprehensive list of organs and tissues was sampled (Supplemental Table 4), and then organs and tissues were fixed in 10% neutral buffered formalin. After 48 to 72 hours of formalin fixation, the organs and tissues were trimmed and processed routinely for light microscopic examination. Specifically, 4-micron thick, hematoxylin and eosin–stained tissue sections were evaluated using an Olympus BX-41 microscope (Olympus).

**Statistics.** Data were analyzed using Microsoft Excel (Microsoft), GraphPad Prism, and Origin softwares (OriginLab). Two-tailed Student’s t tests and analysis of covariance were performed. When multiple t tests were performed, Bonferroni correction was included. P < 0.05 was considered statistically significant.

**Study approval.** Sprague Dawley rats (Charles River Laboratories) and CBA/CaJ mice (The Jackson Laboratory) were used. Animal care and all experimental procedures were carried out in accordance with institutional guidelines at Stanford University.

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