Prominent pancreatic endocrinopathy and altered control of food intake disrupt energy homeostasis in prion diseases

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Abstract

Prion diseases are fatal neurodegenerative diseases that can induce endocrinopathies. The basis of altered endocrine function in prion diseases is not well understood, and the purpose of this study was to investigate the spatiotemporal relationship between energy homeostasis and prion infection in hamsters inoculated with either the 139H strain of scrapie agent, which induces preclinical weight gain, or the HY strain of transmissible mink encephalopathy (TME), which induces clinical weight loss. Temporal changes in body weight, feed, and water intake were measured as well as both non-fasted and fasted concentrations of serum glucose, insulin, glucagon, β-ketones, and leptin. In 139H scrapie-infected hamsters, polydipsia, hyperphagia, non-fasted hyperinsulinemia with hyperglycemia, and fasted hyperleptinemia were found at preclinical stages and are consistent with an anabolic syndrome that has similarities to type II diabetes mellitus and/or metabolic syndrome X. In HY TME-infected hamsters, hypodipsia, hypersecretion of glucagon (in both non-fasted and fasted states), increased fasted β-ketones, fasted hypoglycemia, and suppressed non-fasted leptin concentrations were found while feed intake was normal. These findings suggest a severe catabolic syndrome in HY TME infection mediated by chronic increases in glucagon secretion. In both models, alterations of pancreatic endocrine function were not associated with PrPSc deposition in the pancreas. The results indicate that prominent endocrinopathy underlies alterations in body weight, pancreatic endocrine function, and intake of food. The prion-induced alterations of energy homeostasis in 139H scrapie- or HY TME-infected hamsters could occur within areas of the hypothalamus that control food satiety and/or within autonomic centers that provide neural outflow to the pancreas.

Journal of Endocrinology (2008) 197, 251–263

Introduction

A common hallmark of prion diseases is central and peripheral accumulation of a transmissible pathogenic isoform of a host-encoded prion protein that is partially resistant to proteinase-K degradation (known as PrPSc; Prusiner 1987). Deposition of PrPSc in the brain leads to neurodegenerative changes characterized by a non-inflammatory spongiform encephalopathy (for reviews, see Heikenwalder et al. 2007). Although progressive neurological symptoms are typical of the prion diseases, disruption of endocrine homeostasis has been observed in many instances, including those that have either an acquired, spontaneous, or familial etiology. For example, in scrapie, a prion disease of sheep and goats, hypersecretion of cortisol (Schelcher et al. 1999, Gayrard et al. 2000), growth hormone (Viguie et al. 2004), and insulin-like growth factors (Busiguina et al. 2000) have been observed, as well as altered binding capacity of cortisol-binding globulin (Gayrard et al. 2000). Endocrine alterations in hamsters infected with the 139H strain of the scrapie agent (hereafter, 139H scrapie) have also been reported (Carp et al. 1989, Ye & Carp 1994a,b, 1997, Ye & Carp 1995; for reviews, see Carp et al. 1990, 1994) including obesity, pronounced hyperinsulinemia, altered glucose tolerance and/or insulin resistance (Carp et al. 1989, 1990, Srinivasappa et al. 1989). In mouse models of prion disease, endocrine alterations range from hyperinsulinemia and adrenal-dependent obesity to loss of body weight and reduced adiposity (Carp et al. 1984, 1993, Kim et al. 1987, 1988). In fact, the loss of body weight and adiposity is common in several naturally occurring prion diseases, including sheep and goats with scrapie (Capucchio et al. 2001), in wild ungulates with chronic wasting disease (Miller & Williams 2002; for review see Salman 2003), and in humans with either fatal familial insomnia or Creutzfeldt–Jakob disease (Collinge 2001).

The underlying mechanisms for prion-induced alterations in endocrine homeostasis remain unknown. Evidence from both natural and experimental prion diseases suggest that peripheral endocrine glands (Ye & Carp 1995, 1996, Sigurdson et al. 2001), the hypothalamus (DeArmond et al. 1993), and the brain (Sigurdson et al. 2001) demonstrate varying degrees of PrPSc deposition and/or disease-related pathology by the time neurological symptoms have progressed. However, the spatiotemporal relationship between sites of prion infection and altered endocrine homeostasis has not been established. Because
prion-induced endocrinopathies appear to be associated with control of body weight/adiposity, we hypothesized that energy homeostasis, in general, is subject to prion-induced alteration. We hypothesized, as have others (Ye et al. 1994a,b, 1997), that there are two potential explanations for prion-induced alteration in energy homeostasis: one that involves direct PrPSc infection of peripheral endocrine tissues resulting in altered endocrine gland function, whereas the other involves PrPSc infection of central neuroendocrine tissue and/or the brain stem, resulting in alteration of central mechanisms governing endocrine feedback and/or autonomic regulation of endocrine glands.

To test the hypotheses that 1) prion diseases cause alterations in energy homeostasis and 2) direct PrPSc infection of the pancreas results in alteration of its endocrine function, we used two well-characterized hamster models of prion disease. The 139H scrapie agent causes preclinical obesity in hamsters (Carp et al. 1990, Hecker et al. 1992) and has an incubation period (i.e., the time to clinical disease) that ranges from 20 to 30 weeks (Kimberlin et al. 1989, Hecker et al. 1992, Prusiner 1998). The HY strain of the transmissible mink encephalopathic agent (HY TME) causes wasting at the later stages of clinical disease and has an incubation period that ranges from 8.5 to 9 weeks (Bessen & Marsh 1992, Bartz et al. 2000, 2005). In order to determine whether prion-induced alteration of pancreatic function is related to deposition of PrPSc within the pancreas, we measured fasted and non-fasted concentrations of insulin and glucagon and used western blot analysis to temporally monitor PrPSc infection of the pancreas. Our second objective was to determine whether prion–strain–specific alterations in body weight are accompanied by changes in feed intake, concentrations of hormones known to alter feed intake, and metabolites indicative of energy availability. To achieve this objective, we quantified both fasted and non-fasted concentrations of serum leptin, glucose, and β-ketones throughout disease progression within each prion strain.

Materials and Methods

Animals

Animals used in this study were 6-week-old male Syrian hamsters (Mesocricetus auratus) purchased from Simonsen Laboratories Inc. (Gilroy, CA, USA). Hamsters were habituated to our climate-controlled animal facility (22–24°C, 12 h light:12 h darkness, light onset at 0700 h) for at least 7 days before initiation of the experimentation. Hamsters were allowed to feed ad libitum (Lab chow, Prolab RMH 3000; PMI Feeds, St. Louis, MO, USA) and water except for fasted experiments in which food was removed for ~17 h. On collection days, the terminal sampling procedures were conducted between 0900 and 1100 h. All procedures involving hamsters complied with the Guide for the Care and Use of Laboratory Animals and were evaluated and approved by the Montana State University IACUC committee.

Treatments

At the initiation of each trial (see below), hamsters were i.c. inoculated with 25 µl of 1% brain homogenates (containing 10^5×8 median lethal doses) from either 139H scrapie- or HY TME-infected hamsters. These inocula were obtained previously from the hamsters that had displayed clinical prion disease prior to termination. Control hamsters (hereafter, mock hamsters) received i.c. inoculation with 25 µl of 1% brain homogenate from normal hamsters. Following inoculations, all hamsters were observed thrice per week for clinical symptoms of prion disease. Clinical prion disease was defined as hypersensitivity in response to touch and sound, tremor of the head and shoulders, and ataxia.

Fasted and non-fasted trials and data collection

In order to obtain representative samples for each prion strain, we chose to collect terminal tissue and blood samples throughout the different incubation periods. We arbitrarily chose 25, 50, and 75% of the incubation period as well as the predicted onset of clinical disease in 139H scrapie-infected hamsters. These collection points were estimated to be 5, 10, 15, and 20 weeks p.i. based upon previous research (Kimberlin et al. 1989, Hecker et al. 1992, Prusiner 1998). We chose to take more frequent samples of hamsters inoculated with the HY TME strain since neurological symptoms of prion disease develop more rapidly compared with hamsters inoculated with other strains (Bessen & Marsh 1992). We arbitrarily chose to collect samples at 20, 40, 60, and 80% of the incubation period as well as the predicted onset of clinical disease. These collection points were estimated to be 2, 4, 6, 8, and 10 weeks p.i. based on previous research (Bessen & Marsh 1992, Bartz et al. 2005). At each of the predetermined collection points, a cohort (i.e., sex, time, and age matched) group of mock hamsters was also terminated and sampled in order to provide the comparative data.

In order to obtain enough serum for temporal analyses of changes in hormone/metabolite levels and to evaluate the effects of fasting on endocrine homeostasis, we conducted three different trials (Trial I, Trial II, and Trial III) on either fasted or non-fasted hamsters. In Trial I, data were collected from fasted 139H (n = 20) and mock hamsters (n = 20); in Trial II, from non-fasted 139H (n = 20), HY TME (n = 25), and mock hamsters (n = 45); and in Trial III, from fasted HY TME (n = 15) and mock hamsters (n = 15). Hamsters in Trial I were assigned randomly to cages that were then assigned randomly to a particular treatment. Due to large animal-to-animal variation in initial body weights, hamsters in Trials II and III were stratified by initial body weight and then assigned randomly within strata to treatment, resulting in one large hamster, two medium-sized hamsters, and one small hamster in each cage. Neither age nor body weights were different (P > 0.98; Fisher LSD t-test) among treatments either within or between trials on the day of inoculation.

Tissues were harvested for western blot analysis from the hamsters in Trials I and III while body weights, feed intake,
and water intake were collected weekly from the hamsters in Trial II. Changes in body weights were calculated from individual hamsters, whereas changes in feed intake, gain efficiency, and water intake were calculated from each cage of four hamsters. Gain efficiency was calculated as the ratio of total body weight gained to the amount of food consumed by each cage. On several occasions in Trial II, the number of hamsters within particular cages was diminished compared with all other cages. Therefore, feed and water intake for those cages during those specific weeks were eliminated from the data sets prior to statistical analysis.

**Terminal blood and tissue collections**

After hamsters were overdosed with isoflurane, blood was harvested via cardiac puncture, collected into sterile clot activator tubes (BD Sciences, Franklin Lakes, NJ, USA), and stored at −80 °C until the analysis for hormones and metabolites. Blood tubes were subsequently transported to the laboratory on wet ice and then centrifuged at 4 °C for 30 min at 1800 g (Sorvall-RT6000B, Thermo Electron Corp., Asheville, NC, USA). Serum was collected, vortexed, aliquoted (to eliminate freeze-thaw cycles), and stored at −20 °C until the analyses for hormones and metabolites.

**Glucose tolerance tests – 139H scrapie-infected hamsters**

In order to evaluate obesity-related changes in glucose tolerance of 139H scrapie-infected hamsters, we conducted glucose tolerance tests on six hamsters. After the hamsters were fasted for 17 h, tests were conducted between 0930 and 1130 h (lights on at 0700 h, 12 h light:12 h darkness). Hamsters had been i.c. inoculated 23 weeks earlier with either normal hamster brain (mock) or 139H brain homogenate. All three 139H scrapie-infected hamsters displayed clinical signs of prion disease (severe motor dysfunction and ataxia) at the time of glucose tolerance tests. Hamsters were anesthetized with ketamine (100 mg/kg body weight (BW), i.p.) and kept warm on a heating pad throughout the tests. After a baseline blood sample (0.5 ml) was obtained, glucose was administered intraperitoneally at a dose of 2000 mg/kg BW. Blood samples (0.5 ml) were then obtained at 5, 10, 20, 40, and 60 min post-injection from either the saphenous vein or toenail clipping, collected into sterile capillary spin tubes, and immediately placed at 4 °C. After tests were complete, blood was immediately processed for serum recovery and then frozen at −20 °C until the analysis for glucose and insulin.

**Tissue preparation and purification of PrPSc for gel electrophoresis**

PrPSc purification of tissue was performed prior to western blot analysis as previously described (Bartz et al. 2003, 2005) with modifications based on the work of Herzog et al. (2005). Briefly, tissues were weighed, minced with a razor blade, and mixed with digestion buffer (25 mM HEPES (pH 7.2), 0.3 M sucrose, Liberase Blendzyme 2 (F Hoffmann-La Roche Ltd – Diagnostics Division, Basel, Switzerland), and trypsin inhibitor from soybeans (Sigma–Aldrich Corp.) to a 10% (wt/vol.) mixture and then incubated for 60 min at 37 °C with constant agitation. The mixtures were then passed through a series of needles until completely homogenized and protease activity was stopped by adding complete mini-protease inhibitor (F Hoffmann-La Roche Ltd – Diagnostics Division) and setting samples on ice for 10 min. An aliquot (100–750 µl, depending on tissue) of each homogenate was mixed with an equal volume of buffer (20% (wt/vol.) N-lauroylsarcosine in 10 mM Tris–HCl (pH 7.5)) followed by several rounds of ultracentrifugation as described by Bartz et al. (2003, 2005). The second pellet from these spins was resuspended in a Tris–buffered saline and subjected to sonication using a cup horn sonicator (Fisher Scientific, Atlanta, GA, USA). In order to degrade the normal prion protein (PrP), Proteinase-K (F Hoffmann-La Roche Ltd – Diagnostics Division) was added to a final concentration of 0.4 U/ml and the suspension was incubated at 37 °C for 30 min with constant agitation. Afterwards, phenylmethylsulfonyl fluoride was added to reach a concentration of 1 mM. The third pellet was resuspended in a NuPAGE denaturing buffer and reducing agent and then stored overnight at −20 °C until gel electrophoresis the following day.

**Gel electrophoresis and western blot analysis for PrP immunoreactivity**

Tissue homogenates enriched for PrPSc were subjected to gel electrophoresis for detection of PrP immunoreactivity. Briefly, samples were boiled for 10 min, allowed to come to room temperature, and centrifuged in a microcentrifuge (Eppendorf 5415 D, Eppendorf Corporation, Westbury, NY, USA) at 16 110 g at room temperature for 10 min. Samples were loaded onto 12% Bis–Tris NuPAGE gels (Invitrogen) and ran at 100 V in morpholinepropanesulfonic acid buffer for ~3-25 h. Proteins were then transferred at 30 V for 1 h onto a polyvinylidene difluoride membrane, which were then subjected to a 1 h wash in a 5% (wt/vol.) Blotto blocking buffer (Bio–Rad Laboratories) and then incubated overnight at room temperature with a mouse anti-PrP 3F4 monoclonal antibody (a gift of Victoria Lawson, NIH Rocky Mountain Labs, Hamilton, MT, USA, described by Kascak et al. 1987) at a dilution of 1:40 000 in the above blocking buffer. Following several washes in Tris–buffered saline with Tween-20, blots were subjected to chemiluminescent detection. The detection system included incubation with an anti-mouse immunoglobulin G alkaline phosphatase conjugate (Promega) at a dilution of 1:15 000 in the Blotto buffer. Blots were developed using CDP-Star substrate (Applied Biosystems, Foster City, CA, USA) and imaged with a Kodak Image Station 2000MM and Kodak 1–D software (Eastman Kodak Company).
Hormone and metabolite analysis

Glucose concentrations were determined in duplicate 10 µl aliquots by an end point enzymatic assay using a commercially available glucose determination kit (Infinity Glucose Hexokinase liquid reagent, ThermoElectron Corporation, Waltham, MA, USA). Standard curves were developed using reagent grade d-glucose (Sigma–Aldrich Corp.). Percent recoveries averaged 98±2% when the middle glucose standard (80 mg/dl) was spiked into different volumes of hamster serum. The sensitivity of the assay (absorbance of reagent blank – 2 S.D. of the lowest standard value) averaged 4 mg/dl, and the intra- and inter-assay coefficients of variation were 2.6 and 8.3% for 100 pg/ml, and the intra- and inter-assay coefficients of variation were 4.2 and 6.9% for 100 binding) averaged 110 pg/ml, and the intra- and inter-assay coefficients of variation were 3.6 and 9.4% for 10 µl serum pool from fasted hamsters that inhibited binding of labeled hormone to 58±2% of maximal binding.

Glucagon concentrations were determined in duplicate aliquots of serum (50 or 100 µl, depending upon fasted state) by a commercially available rat glucagon RIA kit (Linco Research, St Louis, MO, USA) validated for use in hamsters in our laboratory. Parallelism between serial dilutions of pooled hamster samples and rat glucagon standards was confirmed. Percent recoveries averaged 98±3% when the middle rat insulin standard (0.5 ng/ml) was spiked into different volumes of pooled hamster serum. The sensitivity of the assay (100% bound concentration − 2 S.D. of maximum binding) averaged 110 pg/ml, and the intra- and inter-assay coefficients of variation were 4-2 and 6-9% for 100 µl of a serum pool from fasted hamsters that inhibited binding of labeled hormone to 58±2% of maximal binding.

The β-ketone concentrations were determined in a single 10 µl aliquot using a commercially available, hand-held glucose/ketone monitor (Precision Xtra, MediSense/Abbott laboratories). Serum was applied to the electrochemical strip, and after 30 s the sensor displayed the concentration of sample β-ketones (mmol/l). Aqueous samples of β-hydroxybutyrate (Sigma) were produced from 0-01 to 10 mmol/l, in order to determine accuracy of the sensor. Linear regression showed that the meter was accurate between ~0-1 and 5 mmol/l (r²=0.951). The maximum read-out value was 6 mmol/l; therefore, the meter’s accuracy above this concentration could not be determined. Percent recoveries averaged 92±2% when the middle ketone standard (0-6 mmol/l) was spiked into different volumes of normal hamster serum.

The lowest concentration of aqueous standard detected by the meter was 0-01 mmol/l. The intra- and inter-assay coefficients of variation were 3-6 and 9-4% for 10 µl of a serum pool from fasted hamsters that had an average readout of 1.4±0.1 mmol/l.

Leptin concentrations were determined in duplicate aliquots of 10 µl serum by a commercially available rat leptin ELISA kit (Linco Research) validated for use in hamsters in our laboratory. Parallelism between serial dilutions of pooled hamster samples and rat leptin standards was confirmed. Percent recoveries averaged 94±3% when the middle rat leptin standard (0-5 ng/ml) was spiked into different volumes of pooled hamster serum. The sensitivity of the assay (absorbance of reagent blank wells − 2 S.D. of the lowest standard value) averaged 0-05 pg/ml, and the intra- and inter-assay coefficients of variation were 2-98 and 4-4% for 10 µl of a serum pool from fasted hamsters that resulted in a net absorbance of 0-143±0.05 units when readings at 590 nm were subtracted from those at 450 nm on an ELISA microplate reader (ELx800, Bio-Tek Instruments, Inc., Winooski, VT, USA).

Statistical analysis

Weekly changes in individual body weight, cage feed intake, cage gain efficiency, and cage water intake, along with terminal serum concentrations of glucose, insulin, glucagon, β-ketones, and leptin were analyzed in separate ANOVA using the generalized linear model approach and the Statistical Analysis System (SAS v. 9-0-3., Cary, NC, USA). Based on the previous data in hamsters (Borer et al. 1979, Rowland 1984) showing that fasting can affect the concentrations of hormones and metabolites of interest, separate ANOVA were constructed for fasted and non-fasted hamsters. Each model included the effects of treatment (i.e. 139H scrapie, HY TME, or mock), time (i.e. weeks p.i.), and the treatment × time interaction. Data from the glucose tolerance tests were analyzed using individual animals as the experimental unit and subjected to repeated measures ANOVA using the generalized linear model approach and the Statistical Analysis System (SAS v. 9-0-3). The effects of treatment, time (i.e. time of sampling), and the treatment × time interaction were included in the model. When the F value indicated a significant effect (P<0.05) in the main ANOVA model, least-square (ls) means procedures were used to calculate means and standard errors. Pairwise t-tests using Bonferroni’s correction for multiple comparisons was used for statistical analysis of the means associated with significant effects. All data reported in this manuscript are lsmeans ± S.E.M.

Results

Incubation periods for 139H scrapie- and HY TME-infected hamsters

In the present study, eight out of ten hamsters (i.e., n=5 from Trial I and n=5 from Trial II) infected with the 139H scrapie strain and killed at 20 weeks p.i. displayed initial signs of prion disease; however, since the studies were terminated at this

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time, a progression of clinical prion disease symptoms could not be verified. Therefore, we could not calculate incubation period data for 139H scrapie-infected hamsters. Previous unpublished data from our laboratory found the incubation period to be 17 ± 0.1 weeks p.i. for 139H scrapie-infected hamsters, similar to the data from Kimberlin et al. (1989) who found incubation periods of ∼18 weeks p.i. However, these data are markedly different from the incubation periods reported by Hecker et al. (1992) and Prusiner (1998), which were 24 and 25 weeks p.i. respectively.

As stated previously, the 139H scrapie-infected hamsters used for the glucose tolerance tests, which were at 23 weeks p.i., displayed clinical symptoms of prion disease including severe motor dysfunction and ataxia. The variation we and other researchers have observed in incubation periods are likely due to differences in the concentration of infectious units in the different inocula, which is known to strongly influence the time required to develop clinical disease symptoms (Hecker et al. 1992). To ensure that the lack of clinical prion disease in the present study was not due to lack of PrPSc deposition, we conducted PrPSc enrichment and western blot analysis of brain tissue collected from three of the 139H scrapie-infected hamsters killed at 20 weeks p.i. Of the three brains analyzed, all were found to be immunopositive for PrPSc (Table 1).

The incubation period for HY TME-infected hamsters was 9.7 ± 0.3 weeks p.i., which is in agreement with previous work (Bessen & Marsh 1992, Bartz et al. 2000, 2005) showing a range of incubation periods from 8.5 to 9 weeks p.i. respectively. Six out of the eight HY TME-infected hamsters killed at 10 weeks p.i. were considered clinical as they displayed severe impairments of motor coordination, head/shoulder tremors, and stimulus sensitive cloni. PrPSc enrichment and western blot analysis of the brains of three of the HY TME clinical hamsters were found to be immunopositive for PrPSc (Table 1).

As predicted, mock hamsters did not show abnormal neurological signs typical of prion disease and evidence of PrPSc deposition in any of the tissues subjected to enrichment and western blot analysis (data not shown).

### Table 1: Spatiotemporal deposition of PrPSc in central and peripheral tissues in hamsters receiving intracerebral inoculation with either 139H scrapie or HY transmissible mink encephalopathy (HY TME)\(^a\)

<table>
<thead>
<tr>
<th>Inoculum</th>
<th>139H Scrapie</th>
<th>HY TME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks p.i.</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>mg (T.E.)(^c)</td>
<td>Percentage of incubation period(^b)</td>
<td>25%</td>
</tr>
<tr>
<td>Tissue</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Brain</td>
<td>Pituitary</td>
<td>0</td>
</tr>
<tr>
<td>SMLN</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Pancreas</td>
<td>50–150</td>
<td>0</td>
</tr>
</tbody>
</table>

p.i., post-inoculation; SMLN, submandibular lymph nodes.
\(^a\)All tissues from mock hamsters were found to be devoid of detectable PrPSc immunoreactivity.
\(^b\)Approximate percent of predicted incubation period that had elapsed.
\(^c\)Amount of tissue subjected to PrPSc enrichment and western blot analysis on a tissue equivalent (T.E.) basis.

Body weight, feed intake, gain efficiency, and water intake in 139H scrapie- and HY TME-infected hamsters

**Body weight** Changes in body weights (Fig. 1A) were not different (P > 0.10) among treatments for the first 8 weeks of the trial. At both 9 and 10 weeks p.i., HY TME-infected hamsters had lower (P < 0.05) body weight when compared with either mock or 139H scrapie-infected hamsters respectively. By 11 weeks p.i., and continuing throughout the remainder of the trial, the 139H scrapie-infected hamsters were heavier (P < 0.05) than the mock hamsters. These data support previous observations (Carp et al. 1990, Ye et al. 1994, 1997, Ye & Carp 1996) in which the 139H strain of scrapie agent caused preclinical obesity in hamsters.

**Feed intake** Cage feed intake (Fig. 1B) did not differ (P > 0.10) among treatments for the first 11 weeks of the experiment. Thereafter, from 11 weeks p.i. to the end of the experiment, 139H scrapie-infected hamsters had greater (P < 0.05) feed intake than mock hamsters. These data are the first to show that 139H scrapie-infected hamsters display increased feed intake relative to time- and age-matched mock hamsters whereas HY TME-infected hamsters maintained normal feed intake for 10 weeks p.i.

**Gain efficiency** Cage gain efficiency (Fig. 1C), which was calculated from the ratio of total body weight gained within a cage to the total amount of food consumed by the cage, did not differ (P > 0.10) among treatments for the first 11 weeks of the experiment. At 9 weeks p.i., the 139H scrapie-infected hamsters had increased (P < 0.05) gain efficiency compared to either HY TME or mock hamsters, for which the gain efficiency was similar (P > 0.01) at this time. From 10 weeks p.i. to the end of the experiment, 139H hamsters had higher (P < 0.05) gain efficiency than mock hamsters. At 10 weeks p.i., HY TME-infected hamsters had diminished (P < 0.05) gain efficiency when compared with either mock- or 139H scrapie-infected hamsters respectively. These data suggest that...
139H-infected hamsters gain more body weight per unit of food consumed when compared with either mock- or HY TME-infected hamsters. Furthermore, by 10 weeks p.i., HY TME-infected hamsters fail to gain weight despite adequate food intake, resulting in negative gain efficiency.

**Water intake** Cage water intake (Fig. 1D) did not differ \((P>0.10)\) among treatments for the first 8 weeks of the experiment. At 9 and 10 weeks p.i., HY TME-infected hamsters had reduced \((P<0.01)\) water intake when compared with either 139H scrapie or mock hamsters respectively. From 11 weeks p.i. to the end of the experiment, 139H hamsters had higher \((P<0.05)\) water intake than mock hamsters. These data suggest that HY TME-infected hamsters develop hypodipsia whereas 139H scrapie-infected hamsters develop polydipsia.

**Endocrine control of energy homeostasis in non-fasted and fasted 139H scrapie-infected hamsters**

**Serum glucose** Non-fasted glucose concentrations did not differ \((P>0.10)\) between 139H and mock hamsters at 5 weeks p.i. At 10, 15, and 20 weeks p.i., non-fasted glucose concentrations were higher \((P<0.01)\) in 139H scrapie-infected hamsters (Fig. 2A) than mock hamsters. Fasted glucose in 139H scrapie and mock hamsters was not different \((P>0.10)\) at 5 or 10 weeks p.i., however, it was higher \((P<0.05)\) in 139H scrapie hamsters at 15 and 20 weeks p.i. respectively (Fig. 2B). These data suggest that 139H scrapie-infected hamsters develop preclinical hyperglycemia, which was most evident during the non-fasted state, which is in agreement with Srinivasappa *et al.* (1989).

**Serum insulin** Concentrations of non-fasted insulin did not differ \((P>0.10)\) between 139H and mock hamsters at 5 weeks p.i. Thereafter, 139H scrapie-infected hamsters had higher \((P<0.01)\) non-fasted concentrations of insulin at 10, 15, and 20 weeks p.i. respectively (Fig. 2C). Concentrations of fasted insulin did not differ \((P>0.10)\) at 5, 10, and 15 weeks p.i. between 139H and mock hamsters. However, at 20 weeks p.i., fasted insulin was higher \((P<0.001)\) in 139H scrapie-infected hamsters than in mock hamsters. The data suggest that 139H scrapie-infected hamsters develop preclinical...
hyperinsulinemia that was accentuated during the non-fasted state. These data are in agreement with several previous studies (Srinivasappa et al. 1989, Carp et al. 1990).

Serum glucagon Non-fasted glucagon concentrations did not differ (P>0.10) between 139H and mock hamsters at any time point evaluated (Fig. 2E). Nevertheless, the treatment effect (P<0.05) indicated that, overall, non-fasted concentrations of glucagon were higher (P<0.05) in 139H scrapie-infected hamsters than in mock hamsters. Similarly, fasted 139H scrapie and mock hamsters had similar (P>0.10) concentrations of glucagon at each time point (Fig. 2F), whereas the treatment effect (P<0.05) indicated that overall 139H scrapie-infected hamsters had lower (P<0.05) fasted glucagon than mock hamsters. These data suggest that 139H scrapie hamsters had higher than normal glucagon secretion during the non-fasted state and diminished glucagon response to fasting.

Serum β-ketones Non-fasted and fasted concentrations of β-ketones were not different (P>0.10) between 139H and mock hamsters at all time points and did not change (P>0.10) over time in either treatment (Fig. 2G and H). These data indicate that oxidation of fatty acids and/or liberation of β-ketones is not altered by 139H scrapie infection in hamsters.

Glucose tolerance tests At baseline, 139H scrapie-infected hamsters displayed higher levels (P<0.05) of glucose when compared with mock hamsters at baseline (Fig. 3A). At 5, 10, and 20 min post-injection, glucose levels increased (P<0.05) in both treatments but did not differ at these time points. However, at 40 and 60 min post-injection, 139H hamsters had higher (P<0.05) glucose compared with mock hamsters. While glucose decreased (P<0.05) in mock hamsters from 20 to 60 min post-injection, there was no corresponding change (P>0.10) in glucose in 139H scrapie-infected hamsters. Serum insulin levels were higher (P<0.05) in 139H compared with mock hamsters at all time points evaluated, including baseline, and did not change over time (P>0.10). Alternatively, mock hamsters showed a temporal pattern of insulin secretion that increased (P<0.05) from baseline to 20 min post-injection, followed by a decrease (P<0.05) from 20 to 60 min post-injection, indicating normal glucostasis (Figure 3B).
These results suggest that the clinical disease in 139H scrapie-infected hamsters is associated with impaired glucose tolerance, insulin resistance, and unresponsive pancreatic β cells.

**Serum leptin** Concentrations of non-fasted leptin did not differ ($P>0.10$) between 139H- and mock-infected hamsters at any time point and did not change ($P>0.10$) over time in either treatment (Fig. 5A). Nevertheless, the overall treatment effect ($P<0.02$) indicated that non-fasted 139H scrapie-infected hamsters had lower ($P<0.05$) concentrations of leptin than non-fasted mock hamsters. Conversely, fasted concentrations of leptin were higher ($P<0.05$) in 139H hamsters than mock hamsters at 10, 15, and 20 weeks p.i. respectively (Fig. 5B). These data suggest that 139H scrapie infection was related to increased levels of leptin during fasting as well as overall diminished levels of leptin during the non-fasted state.

**Endocrine control of energy homeostasis in non-fasted and fasted HY TME-infected hamsters**

**Serum glucose** Non-fasted concentrations of glucose were not different ($P>0.10$) between HY TME and mock hamsters at any time point (Fig. 4A). Nevertheless, the overall treatment effect ($P<0.02$) indicated that non-fasted HY TME-infected hamsters had higher ($P<0.05$) concentrations of glucose than non-fasted mock hamsters. Fasted concentrations of glucose were not different between HY TME- or mock-infected hamsters at 2 or 4 weeks p.i., but were diminished ($P<0.05$) in HY TME-infected hamsters compared with mock hamsters at 6, 8 and 10 week p.i. respectively (Fig. 4B). Nevertheless, the overall treatment effect ($P<0.05$) indicated that the fasted HY TME-infected hamsters had lower ($P<0.01$) glucose concentrations than the fasted mock hamsters. These data suggest alterations in glucostasis in the HY TME-infected hamsters including increased glucose during the non-fasted state, and diminished glucose availability during fasting.

**Serum insulin** Non-fasted concentrations of insulin were not different ($P>0.10$) between HY TME and mock hamsters at 2, 4, 6, or 8 weeks p.i. At 10 weeks p.i., concentrations of non-fasted insulin were higher ($P<0.05$) in HY TME- than mock-infected hamsters (Fig. 4C). Fasted concentrations of insulin in HY TME and mock hamsters were not different ($P>0.10$) at any time point (Fig. 4D). Nevertheless, the overall treatment effect ($P<0.05$) showed that HY TME-infected hamsters had higher ($P<0.02$) fasted insulin than mock hamsters. These data suggest that HY TME-infected hamsters develop non-fasted hyperinsulinemia by clinical disease.

**Serum glucagon** Non-fasted concentrations of glucagon were not different ($P>0.10$) between HY TME and mock hamsters at 2, 4, and 6 weeks p.i. Non-fasted concentrations of glucagon tended ($P=0.06$) to be higher at 8 weeks and were higher ($P<0.01$) by 10 weeks p.i. in HY TME- than mock-infected hamsters (Fig. 4E). Fasted concentrations of glucagon were not different ($P>0.10$) between HY TME and mock hamsters at 2 and 4 weeks p.i., however, they were higher ($P<0.04$) in HY TME-infected hamsters at 6, 8, and 10 weeks p.i. respectively than mock-infected hamsters (Fig. 4F). These data suggest that glucagon levels in HY TME-infected hamsters become chronically elevated during fasting by as early as 6 weeks p.i.

**Serum β-ketones** Non-fasted concentrations of β-ketones were not different ($P<0.05$) between HY TME and mock hamsters at any time point and did not change ($P>0.10$) over time in either treatment (Fig. 4G). Fasted concentrations of β-ketones were not different at 2 and 4 weeks p.i., but were higher ($P<0.02$) in HY TME-infected hamsters than fasted mock hamsters at 6, 8, and 10 weeks p.i. respectively. These data suggest that HY TME-infected hamsters develop a chronic catabolic response to fasting as early as 6 weeks p.i. which continued into clinical disease.

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Serum leptin Non-fasted concentrations of leptin were not different ($P>0.10$) between HY TME and mock hamsters at 2, 4, 6, or 8 weeks p.i. (Fig. 5C) but were lower ($P<0.01$) in HY TME- than in mock-infected hamsters at 10 weeks p.i. Fasted concentrations of leptin were not different ($P>0.10$) between HY TME and mock hamsters at any time point and did not change ($P>0.10$) over time in either treatment. These data suggest that HY TME infection in hamsters results in a diminished leptin response during a non-fasted state.

Analysis of PrPSc content in tissues by western blot

In order to examine whether alterations in pancreatic endocrine function were related to PrPSc deposition in the pancreas, we conducted PrPSc enrichment of pancreata from three out of five hamsters killed at each time point, namely, 5, 10, 15, and 20 weeks p.i. in both 139H scrapie and mock hamsters. PrPSc was not detected in any of the pancreata of 139H scrapie-infected hamsters. Subsequent western blot analysis of a pooled sample of pancreata from 139H scrapie-infected hamsters killed at 20 weeks p.i. again revealed a lack of PrPSc deposition (data not shown). Western blot analyses of tissues from 139H scrapie-infected hamsters revealed preclinical deposition of PrPSc in submandibular lymph nodes by 5 weeks p.i. and pituitary glands by 10 weeks p.i. (Table 1).

Western blot analyses of HY TME hamster pancreata also revealed a lack of pancreatic PrPSc deposition at all time points analyzed (Table 1) and similar results were obtained when samples were pooled (data not shown). Western blot analyses of other tissues from HY TME-infected hamsters revealed PrPSc deposition in submandibular lymph nodes by 4 weeks p.i. and in pituitary glands by 8 weeks p.i. (Table 1).

Discussion

Prion-induced changes in body weight are accompanied by prion strain-specific alterations in energy homeostasis

Our analysis of 139H scrapie and HY TME in hamsters indicate that prior to the development of neurological dysfunction, PrPSc deposition causes complex, strain-specific alterations in energy homeostasis including changes in body weight and disruption of endocrine homeostasis. Importantly, the magnitude of endocrine disruption was affected by fasting status and largely depended upon the stage of infection (i.e., preclinical compared with clinical). Specifically, in the 139H scrapie model, a severe preclinical anabolic syndrome was evident and was more pronounced when hamsters were non-fasted, whereas in the HY TME model a severe catabolic syndrome developed by clinical disease and was more pronounced when hamsters were fasted. Although endocrine data associated with glucostasis are scarce from other prion disease models, sheep with clinical scrapie disease appear to also have increased concentrations of insulin and are also hyperglycemic (Viguie et al. 2004) although scrapie-infected sheep actually lose weight near clinical disease onset (Capucchio et al. 2001).

139H scrapie infection in hamsters induces chronic elevations in insulin, hyperglycemia, and impairs glucose tolerance

The anabolic syndrome that we documented in 139H scrapie-infected hamsters confirms previous observations made by Srinivasappa et al. (1989) and Carp et al. (1990) including preclinical obesity and hyperinsulinemia. However, Carp et al. (1990) further reported that by 18 weeks p.i., fasted 139H scrapie-infected hamsters developed hypoglycemia. This conclusion was based upon a single glucose evaluation at 2 h post-overload compared with the more intensive tests we and others have employed. Data from the glucose tolerance tests conducted by Carp et al. (1990) disagree with our intensive glucose tolerance tests that revealed marked hyperglycemia by 40 min post-overload in clinical 139H scrapie-infected hamsters. Similar glucose tolerance tests performed at 81 days p.i. (~12 weeks p.i.) by Srinivasappa et al. (1989) revealed hyperglycemia by 30 min post-overload. It is difficult to ascertain why there is a discrepancy between the Carp et al. (1990) study and our findings (as well as those of Srinivasappa et al. (1989)), but it could be related to the different methodologies employed (e.g. glucose assays). We evaluated a hand-held glucometer (similar to the one used by Carp et al. (1990) and found unacceptable reproducibility for analytical purposes, a general lack of precision, and an underestimation of glucose when known levels were moderately high (e.g., >160 mg/dl). Therefore, we chose an end point enzymatic assay, as did Srinivasappa et al. (1989), that generated consistent
results over serially diluted, pooled hamster sera and in test samples spiked with very high glucose concentrations (i.e., >640 mg/dl). Overall, the sensitivity, precision and accuracy of glucose determination were vastly improved by utilizing the enzymatic method. The present studies provide strong evidence that impaired glucose tolerance, increased insulin resistance, hyperphagia, and increased gain efficiency in 139H scrapie-infected hamsters are consistent with the observed hyperglycemia. Additionally, the glucose tolerance tests suggest that pancreatic β cells are unresponsive to changes in glucose and/or are chronically stimulated to secrete insulin through a mechanism that may not be directly related to energy status. Regardless, it is our position that these specific alterations in energy homeostasis lead directly to the observed anabolic syndrome and, eventually, cause severe obesity. Importantly, the increased body weights in 139H scrapie-infected hamsters are probably not caused by an overall increase in growth rate, since femur and overall body lengths are not patently different from mock hamsters (Carp et al. 1990).

**HY TME infection in hamsters induces hypersecretion of glucagon and alters glucose availability resulting in increased levels of serum β-ketones during fasting**

We are the first group to describe endocrine alterations that underlie the catabolic syndrome in HY TME-infected hamsters. Alterations in glycosuria were evident in both fasted and non-fasted states. Specifically, modest hyperglycemia was apparent in non-fasted HY TME hamsters whereas glucose levels were diminished in the fasting state. Additional changes included non-fasted hyperinsulinemia at clinical disease in addition to generalized increases in fasting levels of insulin. The paradoxical relationship between suppressed levels of fasting glucose and increased levels of fasting insulin indicate that HY TME infection is associated with severe disturbances in pancreatic endocrine function. In addition, the endocrine and behavioral alterations that normally occur in response to fasting/catabolism, namely compensatory feeding bouts and rapid replenishment of lost energy stores (Borer et al. 1979, Rowland 1984) appear to also be perturbed in HY TME-infected hamsters. In this regard, our data indicate that HY TME infection in hamsters induces a catabolic state that is related to chronic increases in serum glucagon levels, suppressed availability of glucose during the fasted state and, possibly, a failure of compensatory feeding as energy stores become severely depleted. Importantly, the loss of body weight and reduced glucose availability in HY TME-infected hamsters were not the result of diminished feed intake but may be related to diminished efficiency of gain.

Are prion strain-specific alterations of pancreatic endocrine function temporally related to PrPSc deposition within the pancreas?

The western blot analyses showed that despite PrPSc deposition in some peripheral tissues, including the pituitary gland and submandibular lymph nodes, the pancreas did not have detectable levels of PrPSc accumulation in either 139H or HY TME infection. This was surprising given the fact that we analyzed approximately five times more pancreatic tissue when compared with some extra-pancreatic tissues (Table 1). These observations indicate that while peripheral sites of PrPSc infection are evident in both models following i.c. inoculation, these pathways may not be as prominent in the pancreas as in other peripheral tissues. This provides some support for the notion that prion-induced alteration of pancreatic endocrine function is not localized to the islet cells themselves. In part, our results are supported by previous studies using both western blot analysis (Carp et al. 1994) as well as bioassay methodology (Carp et al. 1990, Kimberlin & Wilesmith 1994), which concluded that the pancreas was not a major target of early prion infection. However, low prion titers are present in pancreas from clinical 139H hamsters but are ~6000- to 10 000-fold lower than the titers in brain (Carp et al. 1990, Kimberlin & Wilesmith 1994, Ye et al. 1994a). Since it is not clear when PrPSc deposition occurs in the pancreas of the 139H scrapie-infected hamsters, we can not completely rule out the islet cells as the primary site of prion-induced alteration of pancreatic endocrine function. Clearly, researchers studying 139H scrapie-infected hamsters (using electron microscopy, Ye et al. 1997) and immunostaining procedures (Ye & Carp 1995) have identified PrPSc deposition within pancreata and have described prominent pathological changes specifically within the islet cells (Ye & Carp 1995, Ye et al. 1997) which are reminiscent of increased protein synthesis, enhanced degranulation, and necrosis (Ye et al. 1997). Hamsters receiving i.c. inoculation with a prion strain that does not cause obesity (i.e., 263K) do not develop alterations of pancreatic endocrine function/pathological changes and show no evidence of PrPSc deposition in the pancreas as evaluated by immunohistochemistry (Carp et al. 1994). On the other hand, PrPSc deposition has been documented in islet cells of rodents infected with other strains of prions, yet, alteration of pancreatic endocrine function does not always occur (Kim et al. 1987, Carp et al. 1990, McBride et al. 1992, Kimberlin & Wilesmith 1994, Ye et al. 1994a). Clearly, pancreatic islets contain mRNA for the normal prion protein (Atouf et al. 1994) and are, therefore, theoretically capable of replicating prion infection. However, no studies have established the temporal relationship between PrPSc infection within pancreatic islet cells, histopathological changes, and altered pancreatic endocrine function. In this regard, additional spatiotemporal studies are needed that identify prion-induced pathology within islet cells and evaluate islet cell function at the cellular and/or molecular level.

139H scrapie-infected hamsters appear to have altered leptin sensitivity whereas HY TME-infected hamsters have normal feed intake despite diminished leptin concentrations

Hyperphagia in spite of hyperleptinemia was observed in the 139H scrapie model, which could be the result of strain-specific disruption of the central neuroendocrine systems involved in feed intake regulation. This is suggested because the increased body weights in the 139H scrapie-infected

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Two intriguing possibilities arise with respect to explaining our observations of prion-induced alteration of pancreatic endocrine function and central regulation of leptin-mediated food intake. One involves alteration of brain stem nuclei and autonomic outflow to the pancreas, whereas the other involves alteration of hypothalamic nuclei and neuroendocrine function. The possibility that PrPSc deposition within the hypothalamic causes the observed changes in pancreatic function has been suggested previously (Ye et al. 1994a,b, 1997, Ye & Carp 1995). A study employing stereotaxic injection of a prion strain (i.e. ME7) into the hypothalami of mice caused obesity and perturbations in glucose tolerance, while injection of the same strain into the cerebral cortex did not (Kim et al. 1987). However, as pointed out by Cunningham et al. (2005), the underlying relationship between PrPSc deposition and specific pathology (e.g., spongiform lesions, plaque formation, etc.) within tissues and the resulting effects on cellular function remains elusive. Nevertheless, prion–strain–specific targeting of the hypothalamus has been shown at clinical disease in both hamster and mouse models of prion disease (DeArmond et al. 1993). In one study (Carp et al. 1984), scrapie strains that induced obesity in mice (e.g., ME7 and 22L) also caused intense vacuolation and lesions within the hypothalamus compared with strains that did not cause obesity (e.g., 22A). The observations we have made with respect to altered leptin sensitivity and disregulation of feed intake, as well as the alterations of water intake, may also support the notion of prion–strain–specific targeting. In this regard, the lateral hypothalamic area, paraventricular, ventromedial, and arcuate nuclei appear to be immunopositive for PrPSc deposition at least at clinical disease in 139H scrapie-infected hamsters (Ye & Carp 1996, Ye et al. 1998, Sigurdson et al. 2001). Unfortunately, a temporal study evaluating strain–specific pathology within these areas has not been conducted. Nonetheless, based on classic ablation experiments, these sites are potentially involved in the anabolic syndrome in 139H scrapie-infected hamsters as well as the catabolic syndrome in HY TME-infected hamsters. This is suggested because, in rats, bilateral lesions to several of the listed hypothalamic nuclei induce obesity, hyperphagia and hyperinsulinemia (Bray et al. 1981), whereas a midline stereotaxic lesion that destroys the lamina terminals and preoptic periventricular area produces hypodipsia, yet, feed intake is not compromised (Johnson & Buggy 1978). These studies describe the basic neuroanatomical loci that are the putative targets of prion–strain–specific lesions, which in turn, may underlie the strain–specific alterations in endocrine homeostasis that we have observed.

Since we cannot rule out the pancreas as the primary site of prion–induced alteration in pancreatic endocrine function, it seems appropriate to elaborate on the potential pathways that may be involved therein. Pancreatic islet cells are richly innervated by autonomic nerves (for review, see Ahren 2000) for which the terminals lie in close juxtaposition to the islet cells that secrete either insulin or glucagon (Ahren et al. 1986). Since autonomic disturbances (e.g., cardiovascular dynamics) have been described in other prion diseases (Pomfrett et al. 2004), it is plausible that alterations in parasympathetic or sympathetic outflow to the pancreas may underlie the prion–induced alteration of the pancreas that we have described. The specific pathways may include parasympathetic nerve fibers of postganglionic origin that emanate from intrapancreatic ganglia (Ahren et al. 1986, Brunicardi et al. 1995), which are controlled by preganglionic fibers originating almost exclusively in the dorsal motor nucleus of the vagus (DMNV; Ahren et al. 1986, Berthoud & Powley 1990, Brunicardi et al. 1995). Interestingly, the DMNV is an early target of PrPSc infection in hamsters receiving oral inoculation with the 139H scrapie agent (Beekees et al. 1998), as well as in deer with naturally occurring chronic wasting disease (Sigurdson et al. 2001) and in sheep with clinical scrapie (van Keulen et al. 2000, Ersdal et al. 2003). Several studies show that parasympathetic neurotransmitters are localized to islet parasympathetic nerves, are released directly by vagal stimulation and can induce insulin secretion (Ahren &

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Taborsky 1986). Hence, it is plausible that prion-induced alteration of cell bodies within the DMNV could impact parasympathetic outflow to the pancreas in a manner that causes hypersecretion of insulin, such as in the 139H scrapie model. This may be further supported by our observations of glucose tolerance in 139H scrapie-infected hamsters, which suggest that pancreatic islets are non-responsive to elevated glucose and already maximally secreting insulin even during the fasted state.

Just as parasympathetic neurons mainly stimulate the secretion of insulin, sympathetic neurons mainly stimulate the secretion of glucagon (Ahren & Taborsky 1986, de Jong et al. 1997). Many sympathetic neurons that directly innervate pancreatic islet cells originate as preganglionic cell bodies within the hypothalamus (Ahren & Taborsky 1986, de Jong et al. 1997). Perhaps, the increased glucagon secretion observed in HY TME-infected hamsters could be the result of prion-strain specific alteration of these particular hypothalamic areas in a manner that increases sympathetic outflow to the pancreas. A more detailed analysis of strain-specific PrPSc deposition within the hypothalamus may help elucidate the alterations in pancreatic endocrine function, as well as the marked alterations in water intake we observed. For example, if the sympathetic cell bodies that innervate the pancreas are located in an area of the hypothalamus, which is also known to control water intake in the hamster, the marked hypodipsia that was observed in HY TME-infected hamsters may also be explained by prion-induced pathology at these sites.

In conclusion, the hypothalamus and the brain stem contain neurons that are intimately involved in the control of energy homeostasis and are capable of regulating autonomic outflow to the pancreas and hence secretion of insulin and glucagon. Both sites appear to be targets of PrPSc deposition in a prion-strain-dependent manner. Therefore, it is feasible that an interaction between strain-specific central targeting of 139H scrapie and HY TME and prion-induced pathology within distinct neuroendocrine and/or autonomic pathways could be responsible for the preclinical, strain-specific alterations in energy homeostasis that we observed.

Acknowledgements

The authors would like to thank the staff at the Montana State University Animal Resource Center for excellent animal care. We especially thank Renee Arens for daily care and observations of hamsters. We also thank Rebecca Sorg and Crista Dejoia for their help with tissue collections, animal scoring, and other technical aspects of these studies. Grants that supported this work: United States Geological Survey-BRD National Wildlife Health 30HQRU1516WO-51. National Research Initiative of the USDA. Cooperative State Research, Education, and Extension Service, grant number 2006–35201–16626. US Fish and Wildlife Service grant 1448–60181–03–G739. NIH grant P20 RR–020185–01 from the National Center for Research Resources. The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

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