Raw diets for dogs and cats: a review, with particular reference to microbiological hazards

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There is a recent trend to feed pet dogs and cats in Britain and other developed countries on raw meat and animal by-products using either commercial preparations or home recipes. This shift from heat-treated processed food has been driven by perceived health benefits to pets and a suspicion of industrially produced pet food. The diets of wild-living related species have been used as a rationale for raw feeding, but differences in biology and lifestyle impose limitations on such comparisons. Formal evidence does exist for claims by raw-feeding proponents of an altered intestinal microbiome and (subjectively) improved stool quality. However, there is currently neither robust evidence nor identified plausible mechanisms for many of the wide range of other claimed benefits. There are documented risks associated with raw feeding, principally malnutrition (inexpert formulation and testing of diets) and infection affecting pets and/or household members. Surveys in Europe and North America have consistently found *Salmonella* species in a proportion of samples, typically of fresh-frozen commercial diets. Another emerging issue concerns the risk of introducing antimicrobial-resistant bacteria. Raw pet food commonly exceeds hygiene thresholds for counts of Enterobacteriaceae. These bacteria often encode resistance to critically important antibiotics such as extended-spectrum cephalosporins, and raw-fed pets create an elevated risk of shedding such resistant bacteria. Other infectious organisms that may be of concern include *Listeria*, shiga toxigenic *Escherichia coli*, parasites such as *Toxoplasma gondii* and exotic agents such as the zoonotic livestock pathogen *Brucella suis,* recently identified in European Union and UK raw pet meat imported from Argentina.

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PRACTICE, RATIONALE AND MOTIVATION FOR RAW FEEDING

Feeding products containing raw meat to dogs and cats has become markedly more popular in recent years among pet owners in many developed countries. A large, structured, 2016 survey in the USA indicated that 3% of dog and 4% of cat owners reported purchasing raw pet food, and raw or cooked human food was purchased for pets by 17% of dog owners (APPA 2018). Objective survey data for Europe is lacking, but business and expert opinion indicates similar substantial and growing raw-feeding practices in the UK (Waters 2017).

Raw meat-based diets (RMBDs), sometimes marketed as "Biologically Appropriate Raw Food" or "Bones and Raw Food" (BARF) diets, include uncooked ingredients from either livestock or wild animals and may be home-prepared or commercial, with the latter being supplied as fresh, frozen or freeze-dried complete diets or as premixes intended to be complemented by raw meat (Freeman *et al.* 2013). Raw feeding was given momentum by non-specialist publications in the 1990s and early 2000s (Billinghurst 1993, Freeman & Michel 2001, Towell 2008) that advanced the idea of a more "natural" diet for pet dogs and cats. Claimed benefits, compared with conventional processed diets, are wide-ranging and include improved dental and skin health, prevention or control of disorders affecting any of the major body systems, and behavioural improvements (Towell 2008, Freeman *et al.* 2013, Natures:menu 2017, BARF World 2018).

It has been proposed (Freeman *et al.* 2013) that feeding RMBDs answers a psychological desire among owners to care for and improve their pet's health, using a route that is simple and understandable, compared with more challenging and confusing interventions associated with health professionals. There is also an anti-establishment tone to some articles promoting RMBDs, including sentiment directed against "conventional" pet food manufacturers and the veterinary mainstream (BARF World 2018). Recent survey work comparing attitudes between RMBD- and conventional-feeding pet owners supports the idea that RMBD-feeding owners are less engaged with health specialists (Morgan *et al.* 2017).

EVIDENCE CONCERNING THE BENEFITS OF RAW FEEDING

The wolf has been used as a model by proponents of raw feeding, and much has been made of its limited capacity to digest the carbohydrate that forms a substantial part of conventional dog food. However, the domestic dog is genetically altered from its wild ancestors, with increased starch-digesting capacity owing to different patterns of gene expression (Freeman *et al.* 2013). Other differences between domestic and wild canids include the balance between energy and other nutrient needs, plus longevity (Kölle & Schmidt 2015). These further highlight the limitations of attempting to closely model domestic carnivore diets on those of their ancestral wild counterparts. Furthermore, the relevance of diets eaten in the wild to the health and longevity of domestic and captive mammals may be challenged more broadly. Indeed, contemporary expertise in feeding zoo-kept canids, including wolves, emphasises the benefit of using conventional processed dog food for the majority of the diet (AZA Canid TAG 2012).

A small number of studies have been conducted in an endeavour to provide a verifiable evidence base for some claims made for raw feeding. Faecal bacterial diversity appeared to be higher among six raw-fed dogs compared with five fed conventionally processed food in a metagenomic study (Kim *et al.* 2017). A small feeding trial of boxer dogs comparing raw high-quality beef plus supplement with a commercial dry diet and including metagenomic analysis reported smaller, firmer stools and changes (of unclear significance) in the faecal bacterial community (Sandri *et al.* 2017). Kittens raised on a rabbit-based raw diet also had better stool quality, assessed with a visual grading system, than their commercial diet-fed peers, but both groups grew similarly (Glasgow *et al.* 2002).

Another cat-feeding trial compared a commercial raw diet, a supplemented raw chicken diet and a tinned diet (Hamper *et al.* 2017). Kittens of sequential litters from the same two parents grew similarly on any of the diets, clinical pathology analyses showed minor variations, and diarrhoea was encountered with both raw and cooked diets. Similarly, diarrhoea was neither positively nor negatively associated with raw feeding among dogs used to assist health care (Lefebvre *et al.* 2008). This same, year-long, study noted significantly fewer episodes of extra-intestinal infectious disease among raw-fed dogs, but this was a secondary focus, using owner-reported data and with a modest number (38) of cases. No significant difference was seen for non-infectious disease.

A critical review by Schlesinger & Joffe (2011) concluded that the evidence advanced for the many claimed health benefits of raw feeding amounted to opinions and claims that were, at best, supported by data that was of low relevance. Claims for improved oral health in diets with raw bones find support in studies showing less calculus among feral or wild dogs and cats yet, on balance, the limited published evidence does not support claims of reduced periodontal disease with raw feeding (Steenkamp & Gorrel 1999, Fascetti 2015).

Therefore, aside from some plausible claims for better digestibility and stool quality, the various health claims made for raw feeding remain a mixture of anecdote and opinion, not backed by highly relevant data. This situation is reflected in critical reviews and in advice provided by professional bodies (Schlesinger & Joffe 2011, American Veterinary Medical Association 2012, Freeman *et al.* 2013, World Small Animal Veterinary Association 2015).

CONTROLS ON SOURCE MATERIALS AND PROCESSORS

Source animal species for raw pet foods appear to be diverse (Weese *et al.* 2005, Mehlenbacher *et al.* 2012, van Bree *et al.* 2018). Commercial compounders and suppliers of raw pet food in the European Union (EU) are subject to regulations governing (among other things) animal products not intended for human consumption, principally Regulation (EC) No 1069/2009. Types of these by-products that are permitted in pet food fall into the "Category 3" classification and include those that are fit for, but not intended for, human consumption. Human food containing animal products but removed from the food chain for various reasons (from which no risk to public or animal health arises) can also be classified as Category 3 material (European Commission 2018). In addition, certain by-products that are unfit for human consumption are permitted, provided that the animal was slaughtered in a slaughterhouse and was considered fit for slaughter for human consumption following an *ante mortem* inspection (or the animal was a game species killed for human consumption) *and* that *post mortem* examination did not find evidence of communicable disease (Regulation (EC) No 1069/2009; PFMA 2017). In practice, many producers restrict their animal by-product sources to those fit for human consumption.

EU Animal by-product regulations require commercial producers to perform sampling for *Salmonella* and Enterobacteriaceae according to a site-specific protocol based on batch size and throughput; in the UK, this is in agreement with the Animal and Plant Health Agency (APHA). Detection of any *Salmonella* in samples of product means that it cannot be placed on the market. In the UK, such a finding necessitates notification of the Local Authority and APHA, with the latter supervising the recall and disposal of any affected product, a clean-down of facilities, investigation of the cause and increased frequency of testing (PFMA 2017). In England, there is a derogation allowing animal by-product producers to supply unprocessed material (fit but not intended for human consumption, suitably handled and recorded) direct to individual consumers without being registered or regulated as pet food establishments.

As an example of controls in a major territory outside the EU, microbiologically contaminated animal food is prohibited in interstate commerce in the USA, and Food and Drug Administration advice is for meat ingredients for raw pet food to have been passed for human consumption (Center for Veterinary Medicine 2004). It has been asserted by the American Veterinary Medical Association (2012) that "Raw pet foods are produced with little to no regulatory oversight by the state or federal governments," although the Food Safety Modernization Act of 2011 has gradually introduced further regulation of the pet food sector, with an emphasis on hazard identification and prevention. Nonetheless, derogations exist for small businesses allowing for self-declaration of hazard analysis and preventive controls, without mandatory verification of effectiveness by testing (Center for Veterinary Medicine 2016).

RISKS OF RAW FEEDING

Nutrition

Investigations of both home- and commercially prepared raw diets commonly have identified nutritional problems, such as calcium/phosphorous imbalances and specific vitamin deficiencies (Freeman & Michel 2001, Freeman *et al*. 2013). Moreover, homemade diets are inherently susceptible to nutritional imbalances and deficiencies (Towell 2008). Such diets may be constructed from recipes that do not have verifiable origins in nutritional expertise and feeding studies. Indeed, commercially available raw diets are commonly formulated without the benefit of feeding studies (Mehlenbacher *et al*. 2012). Owners can also be tempted to simplify recipes (Kölle & Schmidt 2015), and ingredients may be poorly defined in the recipe, locally unavailable or of varying quality. There are a few case report studies of clinical nutritional disease associated with raw feeding (Schlesinger & Joffe 2011, Lenox *et al*. 2015).

In the absence of feeding studies for many (if not most) raw diets compounded to be nutritionally balanced, issues of bioavailability pose a further risk of deficiency (Fascetti 2015). This was illustrated starkly in a study using a whole-rabbit raw diet that contained adequate taurine on analysis yet still resulted in taurine-deficiency cardiomyopathy (causing a fatality) among young cats after some months of feeding (Glasgow *et al*. 2002).

Bacterial pathogens

The bacteriological quality of raw commercial pet foods, assessed by total bacterial, coliform or *E. coli* counts, has been noted to fail threshold levels for raw human meat products in a high proportion of sampled foods in both Europe and North America (Freeman & Michel 2001, Weese *et al*. 2005, Kölle & Schmidt 2015, Nilsson 2015, van Bree *et al*. 2018). This, combined with the presence of certain pathogens or antimicrobial-resistant bacteria (summarised in Table 1), poses risks of colonisation and disease for owners and pets alike. It has been noted by researchers sampling raw pet foods from commercial outlets that package warnings about preparation and hygienic handling of these pet foods are commonly absent (Finley *et al*. 2006, Strohmeyer *et al*. 2006, Mehlenbacher *et al*. 2012, Bojanic *et al*. 2017, van Bree *et al*. 2018) and that packaging may be defective and leaky (Bojanic *et al*. 2017).

Salmonella

The transmission of *Salmonella* to dogs and their owners *via* contaminated treats, conventionally processed dry food and raw diets has been observed in a small number of well-investigated incidents (American Veterinary Medical Association 2012; Behravesh *et al*. 2010; Brisdon *et al*. 2006; Clark *et al*. 2001; Cobb & Stavisky 2013; Health Canada 2000; Mayer *et al*. 1976; MDH 2018; Schnirring 2018). Transmission to humans from pet food and treats may be direct in some cases (Pitout *et al*. 2003), and the handling of *Salmonella*-positive food is a well-established risk factor for human salmonellosis (Cobb & Stavisky 2013). However, contact with pets has also been identified as a route or a risk factor for human salmonellosis in several case reports and studies (Finley *et al*. 2006, Domingues *et al*. 2012, Freeman *et al*. 2013), indicating that pets which have consumed *Salmonella*-contaminated feed also pose an infection risk to owners.

Surveys of raw pet foods in North America (generally frozen and obtained through commercial outlets) have reported proportions of *Salmonella*-positive samples ranging between 7.1% (Strohmeyer *et al*. 2006), 8% (Nemser *et al*. 2014), 9% (Mehlenbacher *et al*. 2012), 20% (Weese *et al*. 2005) and 21% (Finley *et al*. 2008). In contrast, just one of 480 (0.2%) conventionally processed dog food samples yielded *Salmonella* in a study from the USA (Nemser *et al*. 2014). A recent study in the Netherlands reported *Salmonella* isolation from 20% of 35 commercial raw food samples (van Bree *et al*. 2018), while in Italy, pork and chicken material available for pet food manufacture yielded *Salmonella* from 12% of samples (Bacci *et al*. 2019). Surveillance of *Salmonella* contamination in pet food by the APHA in the UK (under animal by-products regulations) reported isolations from raw *versus* processed food in ratios of approximately 6:1 in 2015 and 20:1 in 2016, despite most samples coming from the larger processed food sector (APHA 2017). A higher prevalence of *Salmonella* in raw *versus* processed dog and cat foods was also reported in Egypt (Azza *et al*. 2014). Serovars isolated in studies and surveillance of ingredients and raw food for pets or working dogs are diverse (Strohmeyer *et al*. 2006) and include those considered to be of particular significance for human salmonellosis (Chengappa *et al*. 1993, Finley *et al*. 2008, Mehlenbacher *et al*. 2012, Bacci *et al*. 2019). Indeed, in recent years in the UK, more than 50% of such regulated serovar isolations in animal feeding stuffs came from raw pet food, including tripe (APHA 2016, 2017).

Where pet food is contaminated, likely routes of infection for pet owners include contact with the food (when preparing and clearing up pet meals), direct contact with the pet (*e.g.* from

Table 1. Summary of literature cited in "Bacterial Pathogens" section

Organism and references	Details	Sampling detail (number of sampled units)	Detection and identification	Principal findings, including % samples positive
Coliforms				
Weese *et al.* (2005)	Canada	CPF, raw, frozen and freeze-dried (25).	Cult., Sero.	Coliforms: mean 10^6 cfu/g†. *E. coli*: 64%. *Salmonella*: 20%. *Clostridium perfringens*: 20%. *Cl. difficile* 4%. *Staphylococcus aureus* 4%.
E. coli				
Bacci *et al.* (2019)	Including ESBL. Expired human food. Italy	Poultry (52), pork (30) and beef (30), potentially for raw CPF.	Cult., Sero., PCR (ESBL genes)	*E. coli*: 98% samples, MDR in 48% of 110 isolates. *Salmonella*: 13% pork, 12% poultry, 0% beef; of 10 isolates, 80% serovar Typhimurium, 70% MDR, 40% ESBL pheno- and genotype.
van Bree *et al.* (2018)	Including O157:H7, ESC. The Netherlands	CPF, raw frozen (35).	Cult. (bacteria), PCR (protozoa detect.)	*E. coli*: 86%, mean 9×10^2 cfu/g. O157:H7: 23%. ESC: 80%. *Salmonella*: 20%. *Listeria monocytogenes*: 54%. *Toxoplasma gondii*: 6%. *Sarcocystis* species: 23%.
Byrne *et al.* (2018)	Tracing from four linked human STEC O157 cases. England	CPF and ingredients, raw: cases' freezers (2), linked producer (1) and supplier (1).	Cult., PCR, genome sequencing.	STEC: multiple PCR-positive samples from one home and linked producer. STEC O100:H30 from latter. Outbreak isolate not recovered, but much STEC contamination.
Nilsson (2015)	Including ESC. Sweden	CPF, raw frozen (39).	Cult., PCR (typing)	*E. coli*: 49% > 5×10^2 cfu/g†; 5% > 5×10^4 cfu/g; ESC: 23% bla_{cmy2}.
Azza *et al.* (2014)	Egypt	Pet food: raw (20), not raw (40).	Cult.	*E. coli*: 35%. *Salmonella*: 5%. *S. aureus*: 15%. All from raw.
Nemser *et al.* (2014)	O157:H7 and STEC, USA	CPF: raw (196), dried treats (190), not raw (480).	Cult., PCR (STEC)	No O157:H7. Raw (mostly frozen): STEC 4%, *Salm*. 8%, *Listeria* species 33%, *L. monocytogenes* 16%. Dry: STEC 1.1%, Listeria species 0.5%. Not raw: *Salm*. 0.2%, *Listeria greyii* 0.2%.
Lenz *et al.* (2009)	O157, USA	Pet dogs (91), 42 raw-fed, matched faeces and food.	Cult., Sero.	*E. coli* O157: No isolations. *Salm*.: 14% raw-fed dogs, 5% raw food samples; no other isolations. *Campylobacter jejuni*: 1 isolation from raw-fed dog.
Lefebvre *et al.* (2008)	Including ESC. Health care assistance dogs, Canada	Dogs (194), 40 raw-fed raw. Faeces and nasal swabs, bi-monthly for 1 year.	Cult., Sero.	Point prevalence ranges (% dogs): ESC *E. coli* (AmpC-type) raw 15 to 45 *versus* non-raw 0.9 to 9.7; *Salm*. raw 2.5 to 25 *versus* non-raw 0 to 2.6. VRE: 1 isolate; ESBL no isolations. All dogs shedding *Salm*. >1 occasion were raw fed. MRSA and *Cl. difficile*: no association with raw feeding.
Strohmeyer *et al*. (2006)	USA	CPF, raw frozen (240), not raw (48).	Cult. (bacteria), PCR (protozoa detect.)	*E. coli*: 60% raw, 33% dry, 8.3% canned. *Salmonella*: 7.1% raw, *Cryptosporidium*: 0.8% raw, 4% canned.
Freeman & Michel (2001)	O157:H7, USA	CPF, also home-made and meat plus additive, all raw (5).	Cult.	One *E. coli* O157:H7 isolate, no *Salmonella*.
See also Weese *et al*. (2005) (under "Coliforms")				
Salmonella				
MDH (2018)	Link to human *Salm*. Reading cases, USA	CPF, raw, ground turkey (1).	Cult.	*Salmonella* Reading (1/1).
Reimschuessel *et al*. (2017)	Laboratory submissions, USA	Pet dog (2422) and cat (542) stools, 50% diarrhoeic.	Cult., Sero.	Raw-fed dogs over-represented among *Salmonella*-positive cases (P=0.03, multiple regression). Cats rarely *Salmonella* positive.
Kantere *et al.* (2016)	Greece	Dogs (120), 60 raw-fed; oral plus faecal swabs.	Cult., Sero.	*Salmonella* only from raw-fed dogs (18%). Various serovars, antimicrobial resistances common.
Mehlenbacher *et al*. (2012)	USA	CPF: raw frozen (29), dehydrated and freeze-dried (31), not raw (5).	Cult., Sero.	14% of frozen raw, four serovars.
Leonard *et al.* (2011)	Canada	Pet dogs (138), 28 raw-fed. Faeces, 5 consecutive days.	Cult., Sero.	50% raw-fed dogs *versus* 16% not raw-fed; raw feeding only significant risk factor for shedding in series of univariable models.
Behravesh *et al*. (2010)	Investigation of human cases, USA	Faeces of cases' pet dogs (≥15), dry dog and cat food (multiple), feedmill samples.	Cult., PFGE	S. Schwarzengrund of outbreak PFGE pattern isolated from six of 15 dog stool samples and four brands of dog and cat food from same feedmill, plus one location within the mill. Mostly young children infected, risk factor of feeding pet in kitchen in univariable case-control study.
Finley *et al.* (2008)	Canada and USA	CPF, raw frozen (166).	Cult.	21%, up to five serovars *per* sample, some multi-resistant. Chicken-containing diets more likely (5×) to yield *Salmonella*.
Finley *et al.* (2007)	Naturally contaminated raw food.	Faeces, 16 experimentally fed dogs. Daily sampling.	Cult., Sero.	Seven dogs shed *Salmonella*, for range 1 to 11 days. Two of these shed a serovar different from that isolated from the food.
Brisdon *et al.* (2006)	Trace-back from three human cases	Dog treats, link to cases by brand or premises.	Cult., PFGE	Indistinguishable subtypes of S. Thompson from humans and pet treats in all cases.

Table 1. (Continued)

Organism and references	Details	Sampling detail (number of sampled units)	Detection and identification	Principal findings, including % samples positive
Morley *et al*. (2006)	Dog kennels, salmonellosis. Food mixed on site. USA.	Food in bowls (3), frozen beef (18), environment swabs (31), dog faeces (61).	Cult., Sero., PFGE	Isolates from 100% food in bowls, 33% beef, 93% faeces, 48% swabs. Predominantly S. Newport including all meat isolates. Multiple subtypes, overlap between beef, faeces and environment isolates.
Weese & Rousseau (2006)	Bowl hygiene study using spiked food.	Swabs, after contamination of bowl surfaces and drying.	Cult.	Proportion of bowls with viable *Salmonella* Copenhagen after: 7 days (100%), 85 °C dishwasher cycle (67%) or scrubbing with soap (79%) followed by bleach soak (42%).
Pitout *et al*. (2003)	Link to human cases in ESC *Salm*. cluster	Dog treat: dried beef (1).	Cult., Sero., PFGE	ESC, PFGE pattern identical to some and similar to others from human S. Newport ESC cases.
Joffe & Schlesinger (2002)	Food and recipient dog study. Canada	CPF: raw chicken-based (10) and not raw (10). Dog faeces (20).	Cult., Sero.	Food, raw: 80%, various serovars. Faeces, raw-fed, 30%. No other isolations.
Clark *et al*. (2001)	Canada	Treats: pig ear (265), other (39).	Cult., PFGE, PT	Pig ears: production plant 29% and retail 51%. Other treats: 38%. Several serovars.
Hea (2000)	Trace-back from human case. Canada	Pig ear treat from linked premises.	Cult., PFGE, PT	S. Infantis: same serovar, phage type and PFGE pattern as human case.
Mayer *et al*. (1976)	Raw-fed police dogs, Germany	Faeces, dogs (67), three occasions.	Cult.	First sampling: 42% shedding *Salm*. Thereafter, diet was cooked, but 69% dogs fed raw offal by handlers. Second sampling: 55% shedding, more serovars reflecting local pig carriage.
See also Weese *et al*. (2005) (under "Coliforms"); Bacci *et al*. (2019), van Bree *et al*. (2018), Azza *et al*. (2014), Nemser *et al*. (2014), Lenz *et al*. (2009), Lefebvre *et al*. (2008), Strohmeyer *et al*. (2006) and Freeman & Michel (2001) (under "*E. coli*")				
Campylobacter				
Bojanic *et al*. (2017)	New Zealand	CPF, raw (50); rectal swabs, dogs (90), cats (110).	Cult., PCR (speciation), MLST.	*Campylobacter* species: food, 28%; dogs 36%; cats 16%. *C. jejuni*: food 22%; dogs 13%; cats 5%; several MLST types shared between food and pets.
See also Weese *et al*. (2005) (under "Coliforms"); Lenz *et al*. (2009) and Strohmeyer *et al*. (2006) (under "*E. coli*")				
Yersinia enterocolitica				
Bucher *et al*. (2008)	Germany	Faeces, various species; pig tissues (tonsil, edible offal, pork), other livestock tissues.	Cult., PCR (detection)	Tissues, culture: pig offal 51%, pork 9.6%. Tissues, PCR: pork 8.3%, sheep tonsil 3%, poultry 1%, game 38%. Faeces, PCR: dog 5%, cat 3%.
Fredrikkson-Ahomaa et al. (2001)	Biotype 4/O:3 isolates study, Finland	Faeces: dog (12) and cat (4). Pig: abattoir (75) and retail (41).	PFGE	PFGE patterns of dog and cat isolates, including known raw-fed animals, overlap with those from pig-derived food.
Brucella suis				
Frost (2017)	Netherlands and UK	Raw frozen hare meat, imported from Argentina for pet food.	Technique(s) not described	Identified following trace-back from *B. suis* infection of raw-fed dog in Netherlands.
Listeria				See Azza *et al*. (2014), Nemser *et al*. (2014) and van Bree *et al*. (2018) under '*E. coli*'
Staphylococcus aureus				See Weese *et al*. (2005) under "Coliforms"; Lefebvre *et al*. (2008), Azza *et al*. (2014), Nemser *et al*. (2014) and van Bree *et al*. (2018) under "*E. coli*"
***Enterococcus* species (VRE)**				See Lefebvre *et al*. (2008) under "*E. coli*"
Clostridia				See Weese *et al*. (2005) under "Coliforms"; Lefebvre *et al*. (2008) under "*E. coli*"

CPF commercial pet food, Cult. culture, ESBL extended-spectrum beta-lactamase producer, ESC extended-spectrum cephalosporin-resistant, Incl. including, MDR multi-drug resistant (resistant to ≥3 antimicrobial drug classes), MLST multi-locus sequence typing, MRSA methicillin-resistant *Staphylococcus aureus*, PCR polymerase chain reaction, PFGE pulsed-field gel electrophoresis, PT phage typing, Sero. serotyping, STEC shiga toxigenic *E. coli*, VRE vancomycin-resistant enterococci
†Exceeding Canadian Food Inspection Agency coliform limit for raw meat (10^3 cfu/g)
‡European Union limit for minced meat for human consumption

licking) and contact with *Salmonella* shed in pets' faeces. Hazard labelling on commercial raw foods may be poor, as discussed previously. Trials of domestic cleaning and disinfection routines have shown them to be ineffective at eliminating *Salmonella* contamination from bowls (Weese & Rousseau 2006), while *Salmonella* contamination of surfaces was prevalent in a raw-feeding kennel establishment despite good daily cleaning routines (Morley *et al.* 2006).

The frequency of faecal shedding of *Salmonella* by dogs fed raw diets correlates with the *Salmonella* risk of the food material in many studies (Joffe & Schlesinger 2002, Finley *et al.* 2007, Lefebvre *et al.* 2008, Lenz *et al.* 2009, Kantere *et al.* 2016). Indeed, studies in dogs have identified raw feeding as a major risk factor for *Salmonella* shedding (Leonard *et al.* 2011, Reimschuessel *et al.* 2017). The shedding of *Salmonella* by raw-fed dogs appears to occur at a similar or higher frequency than the ingestion of identifiably contaminated pet food (Lenz *et al.* 2009, Leonard *et al.* 2011), suggesting that *Salmonella* ingestion commonly leads to chronic or amplified shedding in dogs. This notion is supported by longitudinal monitoring demonstrating shedding for 1 to 11 days after 1 day of feeding *Salmonella*-contaminated commercial raw food (Finley *et al.* 2007). Diarrhoea does not appear to be a typical feature of *Salmonella*-shedding dogs (Brisdon *et al.* 2006, Finley *et al.* 2007, Reimschuessel *et al.* 2017), although clinical salmonellosis has been reported in association with raw feeding (Morley *et al.* 2006).

Salmonella serovars shed by raw-fed dogs correlate with those isolated from their pet food (Mayer *et al.* 1976, Joffe & Schlesinger 2002, Morley *et al.* 2006, Finley *et al.* 2007), and these food isolates, as already discussed, include serovars associated with human disease. Furthermore, such human-associated serovars have commonly been isolated from the faeces of dogs (Reimschuessel *et al.* 2017), including raw-fed dogs (Lefebvre *et al.* 2008, Lenz *et al.* 2009, Leonard *et al.* 2011).

Pet-owning households commonly include humans with a higher risk of contracting *Salmonella* infection from pets, whether by virtue of poor hygiene observance around animals (*i.e.* young children) or other factors such as advanced age and immunocompromise (Stull *et al.* 2013). However, human clinical disease associated with exposure to raw-fed pets and their food is likely to occur as sporadic and isolated cases rather than in outbreaks. Therefore, such cases typically will not feature prominently, or at all, in public health reports (Finley *et al.* 2006, American Veterinary Medical Association 2012), unless in the context of a wider outbreak (CDC 2018a).

Outbreak investigations have been conducted for human salmonellosis cases relating to a contaminated dry dog food manufacturing plant (Behravesh *et al.* 2010) and to the use of frozen "feeder rodents" for pet reptiles (Cartwright *et al.* 2016, Kanagarajah *et al.* 2018). These provide firm supportive evidence for the zoonotic risk of feeding *Salmonella*-contaminated products to pets, and in the investigation by Behravesh *et al.* (2010), the risk to young children appeared to be disproportionately high. In view of the perceived risk of human infection, some public health bodies have published advice on the safe handling of raw pet food to mitigate such risks in the home (FDA 2018, CDC 2018b).

E. coli

E. coli typically lives as a commensal enteric species, and strains may transfer between pet dogs and their owners (Naziri *et al.* 2016). Pet food diets often contain viable *E. coli*, reflecting their universal presence in large numbers within the intestinal tracts of source animal species and the ease with which faeces may contaminate many plant ingredients *via*, for example, wildlife and water. Higher prevalence values of *E. coli*-positive samples have been found among commercial raw pet foods when compared with conventionally processed foods (Strohmeyer *et al.* 2006, Freeman *et al.* 2013). Numbers of *E. coli* in frozen raw pet food commonly exceed EU limits for minced meat destined for human consumption, sometimes by two or more orders of magnitude, and also exceed the EU absolute threshold (5×10^3 cfu/g; Commission Regulation (EU) No 142/2011) for raw pet food at the point of production (Nilsson 2015, van Bree *et al.* 2018).

Some subtypes of *E. coli* are pathogenic, elaborating certain colonisation factors and toxins. The shiga toxin-producing *E. coli* (STEC; often of serovar O157:H7) are a prominent contemporary example in the human field. STEC O157:H7 was isolated from some raw diets, around 20% of samples, in a recent survey from the Netherlands (van Bree *et al.* 2018). However, serogroup O157 was not isolated from a total of 616 raw food samples in two studies in the USA (Lenz *et al.* 2009, Nemser *et al.* 2014). Such differences may reflect variation in local meat contamination, types of source meat and investigators' methodology. A recent investigation in the UK identified closely related STEC O157 isolates from four human clinical cases, including three children under 10 years old, and with one fatality (Byrne *et al.* 2018). In three of these cases, a link with dogs on a raw diet was established.

Campylobacter species

Campylobacter were not isolated from approximately 300 samples taken from raw food products in various recent studies in the USA and Canada (Weese *et al.* 2005, Strohmeyer *et al.* 2006, Lenz *et al.* 2009). Chicken ingredients might be considered likely sources of *Campylobacter* given the well-documented high prevalence of carcass contamination (Suzuki & Yamamoto 2009, Gonçalves-Tenório *et al.* 2018). However, the sensitivity of the organism to drying, freezing and oxygen, plus relatively insensitive bacteriological detection methods, means that its apparent absence from prepared foods is perhaps not surprising. In contrast, Bojanic *et al.* (2017) isolated *Campylobacter jejuni* from 22% of raw retail pet foods in New Zealand. In the same study, univariable analysis showed an association between *Campylobacter upsaliensis*-positive rectal swabs and wet (but not specifically raw) feeding among both dogs and cats.

It is likely that a small proportion of human campylobacteriosis cases are acquired through contact with pets. Evidence for this includes risk factor analyses (Damborg *et al.* 2016), the tendency for asymptomatic and intermittent or extended shedding of human-pathogenic *Campylobacter* bacteria by young dogs (Hald *et al.* 2004, Parsons *et al.* 2011) and several case studies where zoonotic transmission has been inferred (Damborg *et al.* 2016). In one such case, raw feeding of puppies with chicken by-products was documented (Campagnolo *et al.* 2018).

Listeria monocytogenes

This organism causes serious disease in many species, including humans, but rarely among dogs (Pritchard *et al.* 2016). *Listeria monocytogenes* was isolated from 54% of Dutch products sold as frozen raw pet food (van Bree *et al.* 2018) and from 16% of raw (usually frozen) dog and cat foods in the USA (Nemser *et al.* 2014). None of the 480 conventionally processed dry and semi-moist pet foods in the latter study yielded the organism.

Yersinia enterocolitica

This is a well-recognised cause of human enteritis, with occasional serious sequelae, in Europe and elsewhere (EFSA & ECDC 2017). The organism survives freeze-thawing (Toora *et al.* 1992) and is common in raw pork, pig offal and game meats (Bucher *et al.* 2008). Dogs and cats shed human-pathogenic bioserotypes (Bucher *et al.* 2008), and PFGE subtyping has implicated contaminated pork products as an original source for such shedding (Fredriksson-Ahomaa *et al.* 2001). Therefore, improper handling of contaminated meat (including pig offal) is thought to be a major risk for human yersiniosis, whilst a minor proportion of cases may derive from contact with pets (Fredriksson-Ahomaa *et al.* 2006).

Brucella species

Species of the genus *Brucella*, while linked to their principal hosts, do not appear to be strongly host-restricted. Indeed, several, including *Brucella abortus*, *Brucella melitensis*, *Brucella canis* and *Brucella suis*, are zoonotic (Woldemeskel 2013). *B. suis* is principally identified as a cause of brucellosis in feral pigs, but where dogs commonly encounter or hunt wild pigs or consume pig meat (such as in parts of Australia), clinical orthopaedic and reproductive disease in dogs associated with the organism is recognised (Mor *et al.* 2016). *B. suis* has a low infectious dose for humans, and zoonotic disease is often acquired through butchering or consuming wildlife (Woldemeskel 2013), although transmission to humans from dogs *via* secretions and urine is considered to be possible under favourable circumstances (Neiland & Miller 1981). *B. suis* was recently found in frozen hare meat imported from Argentina into the Netherlands and the UK for raw pet diets, being identified following clinical disease in an exposed dog (Frost 2017).

Miscellaneous

Various other potentially pathogenic bacterial entities have been either identified in raw pet diets (*Staphylococcus aureus*, *Clostridium* species) or considered potential disease risks from source livestock (*Bacillus cereus*, *Bacillus anthracis*, *Burkholderia* species), especially if food is left at ambient temperature before consumption (LeJeune & Hancock 2001, Weese *et al.* 2005, Burns 2012). However, the magnitude of risk posed by these organisms is currently unknown. O'Halloran *et al.* (2018) have suggested the possibility of indoor domestic cats being infected by *Mycobacterium bovis via* raw feeding, although evidence of infection and of transmission route(s) in the cited cases remains uncertain (Middlemiss & Clark 2018).

Antimicrobial resistance

The risk that raw feeding might enhance the spread of antimicrobial-resistant bacteria has been considered by several investigations. Heat treatment is a critical control step in the elimination or marked reduction of bacteria arising from livestock sources, which is not available to producers of raw food. Both pathogenic and commensal bacterial species from livestock may carry antimicrobial-resistance genes, some of which can be readily transmissible.

Extended-spectrum beta-lactamase (ESBL) resistance is typically borne on transmissible plasmids and is currently common among *E. coli*, and other Enterobacteriaceae, in poultry production in Europe and elsewhere (Scientific Advisory Group on Antimicrobials of the Committee for Medicinal Products for Veterinary Use 2009). ESBL and the related AmpC-type resistance confer reduced susceptibility to extended-spectrum cephalosporins, these being considered of critical importance in human medicine (WHO 2016). A study in the Netherlands reported that 28 of 35 raw pet food products yielded ESBL-positive *E. coli* (van Bree *et al.* 2018), while in Italy, ESBL producers were prevalent among *Salmonella* isolates from date-expired human products available for pet food use (Bacci *et al.* 2019). A second Dutch study also found that a similar proportion of raw products (14 of 18) yielded ESBL- or AmpC-positive Enterobacteriaceae compared with none of 35 processed products (Baede *et al.* 2017), whilst 23% of Nordic raw food samples containing poultry meat yielded plasmid-borne AmpC genes (Nilsson 2015).

This apparently elevated risk of extended-spectrum cephalosporin resistance compared with heat-treated food, coupled with the previously discussed evidence for relatively high counts of *E. coli* and related organisms in raw food, appears to translate into an increased risk of the presence, or of heavy shedding, of resistant organisms. There was a strong association between raw feeding and the likelihood of faecal shedding of *E. coli* exhibiting AmpC-type resistance among therapy dogs in Canada over the course of 18 months (Lefebvre *et al.* 2008). Two Dutch longitudinal studies reported associations between raw feeding and faecal *E. coli* from dogs showing ESBL resistance (Baede *et al.* 2015) or faecal Enterobacteriaceae from cats showing ESBL/AmpC resistance (Baede *et al.* 2017). This last study also found that, where phenotypically resistant Enterobacteriaceae were isolated, the mean count (colony-forming units *per* gram faeces) for such isolates among raw-fed cats was over two orders of magnitude higher than among controls.

In two cross-sectional studies of dogs in the UK, associations with raw feeding were found for AmpC phenotype *E. coli* (Schmidt *et al.* 2015) and for third-generation cephalosporin-resistant *E. coli* (Groat *et al.* 2016). Another UK cross-sectional study reported a strong association between feeding raw poultry and faecal ESBL *E. coli* among veterinary-visiting dogs (Wedley *et al.* 2017).

In addition to ESBL/AmpC resistance studies, raw feeding has also been identified as a risk factor for faecal shedding by dogs of *E. coli* exhibiting other antimicrobial drug resistances (Leonard *et al.* 2015, Groat *et al.* 2016). This is similar for resistant *Salmonella* (Leonard *et al.* 2015) or for multi-drug-resistant *E. coli* (Groat *et al.* 2016, Wedley *et al.* 2017). Greyhounds fed on raw meat were also found to commonly shed multi-resistant strains of *Salmonella* (Morley *et al.* 2006), and multi-resistant *S.* Reading has been isolated from raw pet food and from two infected in-contact children (MDH 2018, CDC 2018a).

Multi-resistant *E. coli* and *Salmonella* strains were prevalent among poultry and pork material available for pet food manufacture in Italy (Bacci *et al.* 2019), and there is a particular concern in the UK about the use of imported poultry meat for RMBDs. The consumption by dogs and cats of multi-resistant epidemic *Salmonella* serovars (such as *S.* Kentucky, *S.* Infantis, *S.* Stanley, *S.* Heidelberg and ciprofloxacin-resistant *S.* Enteritidis) that are not currently present in UK food animals (EFSA 2012, Springer *et al.* 2014, Shah *et al.* 2017) pose a risk of the subsequent incursion of such resistant strains into British poultry flocks *via* pets shedding the organisms. Free-range flocks with public footpaths across range areas and poultry farms with resident dogs are particularly at risk.

Non-bacterial pathogens and zoonoses

Several helminths and protozoa have been proposed as potential pathogenic risks for raw-fed cats and dogs and/or for in-contact owners and livestock. These include: *Neosporum caninum*, *Sarcocystis* species, *Toxoplasma gondii*, *Isospora* species, *Cryptosporidium parvum*, *Giardia*, *Echinococcus granulosus*, *Echinococcus multilocularis*, *Taenia hydatigena*, *Taenia ovis* and *Trichinella* species (LeJeune & Hancock 2001, Macpherson 2005, Silva & Machado 2016, van Bree *et al.* 2018). There are well-characterised risks to humans or livestock from pets shedding some of these strains, but useful data on the risks posed by raw pet food with respect to these organisms is sparse. The commonly practiced freeze-thawing of raw diets will have a pronounced detrimental effect on protozoa and helminths in contrast with many bacteria, although effects vary by organism and by the temperature and duration of freezing (PFMA 2017).

For *T. gondii,* there is an established zoonotic risk from infected cats. Moreover, raw-fed cats have been shown to demonstrate increased toxoplasma seroprevalence and oocyst shedding (Lopes *et al.* 2008, Coelho *et al.* 2011, Freeman *et al.* 2013), but there is also a potential direct infection route to humans from raw meat (Macpherson 2005). PCR techniques detected *Sarcocystis* and *Toxoplasma* in a minority of Dutch raw food samples (van Bree *et al.* 2018). Similarly, DNA of *Cryptosporidium* (but not *Toxoplasma* or *Neosporum*) was found in a small minority of raw and canned foods in the USA (Strohmeyer *et al.* 2006). In none of these cases was the viability of the protozoa established.

There are few previously published comments concerning potential issues with viral pathogens in raw pet foods. Cases of pseudorabies virus infection have been reported in cats and dogs after ingesting meat from affected pig herds (Hoorens 1978, Kotnik *et al.* 2006) and, similarly, dogs appear susceptible to African Horse Sickness after ingesting meat from clinically affected horses (O'Dell *et al.* 2018). Rabies and hepatitis E are viruses that may infect the tissues of source animals for raw food, and there are data suggesting a risk to pets and/or their owners following ingestion (Bell & Moore 1971, Meng 2005). However, such risks are as yet unproven. Virus contamination introduced at processing plants might also pose a risk to pet owners. The human norovirus has potential for such a role as it is common, is shed heavily by infected individuals during acute illness and, moreover, it survives passage through the canine gastrointestinal tract (Summa *et al.* 2012). While the risks of virus contamination may not be unique to raw diets, the potential of conventional processing to effect elimination or marked reduction in viability has been demonstrated, at least for a veterinary calicivirus (Haines *et al.* 2015).

SUMMARY

The use of raw diets is a growing phenomenon among pet owners in developed countries, who in previous decades had embraced the nutritional expertise and convenience offered by processed pet food industries. There is a polarisation in the public debate on the merits of raw feeding, touching as it does on emotionally charged issues such as the care and welfare of pets and a countercultural response to perceived vested interests in the animal feed and other pet care industries. Anecdote, endorsement and firmly expressed opinion have been used on both sides of the debate, and the "campaigning" tone has been aided by large gaps in data.

Given the typical differences between the balance of nutrient groups in raw and processed foods, it is perhaps not surprising that formal investigations have pointed to differences in the gut microbiome between raw- and conventionally fed animals, nor that, anecdotally, owners report differences in stool quality. Formal data on a limited number of apparently healthy individuals does not suggest an association between raw feeding and a reduction in periodic episodes of diarrhoea. Nonetheless, it is plausible that, for certain individuals and certain diets, raw feeding may lead to improvements in clinical signs relating to, for example, food intolerances, inflammatory bowel conditions and some other conditions in which dietary influences have been established. What appears less plausible, from a scientific standpoint, are the very broad benefits claimed for raw feeding (without formal evidence) with respect to an extensive range of inflammatory, infectious, neoplastic, endocrine, behavioural and other conditions. Such claims cannot be made directly by manufacturers and retailers in territories where there are stringent evidence rules for commercial advertising. Nonetheless, anecdotes and personal endorsements implying such benefits are promoted in company communications (Natures:menu 2017, BARF World 2018).

With respect to the potential adverse effects of raw feeding, evidence of risk is mostly piecemeal in nature and commonly fails to demonstrate tangible consequences of the identified hazard. Thus, warnings of risks remain susceptible to being dismissed as "scare stories" by proponents of raw feeding. However, there is a growing body of formal investigations and peer-reviewed publications documenting various aspects of risk and adverse effects associated with raw feeding, although outcomes are still largely documented as case reports or in the context of small studies. There appears little doubt from survey evidence that the prevalence of potentially serious pathogens is substantially higher in raw pet food than in heat-treated food. Most evidence in this respect has accrued for *Salmonella* risk. Whilst targeted and systematic monitoring of households may yet be needed to quantify the human health hazards of raw feeding, human salmonellosis outbreak investigations in related situations (contaminated pet treats and dry food, rodent carcasses for feeding reptiles) have clearly demonstrated the risk.

On a precautionary basis, the advice against raw feeding issued by various professional bodies appears justified, especially in the case of the many households that include individuals especially vulnerable to infectious disease. In addition, aspects of raw feeding that may have been underappreciated until recently include the increased frequency and number of antimicrobial drug-resistant bacteria in raw foods and the risk of exotic pet, livestock and zoonotic diseases associated with imported raw meats.

In conclusion, there is much in the current movement for raw feeding of pets that follows a pattern of counter-establishment beliefs (appealing variously to ideas of simplicity, intuition and contrarian enlightenment), which are also recognised in many other fields. Such beliefs often use the language and style of formal science while using emotive rationales and relying on anecdote and highly selective data and interpretations as an evidence base. The subsequent development of business and marketing strategies for raw feeding may reinforce a public perception of the reliability of claims made.

Currently, data for the nutritional, medical and public health risks of raw feeding are fragmentary, but they are increasingly forming a compelling body of formal scientific evidence. It appears important that veterinary and public health practitioners and organisations continue to exercise a responsibility to communicate this to both consumers and producers of raw pet food. Given that raw feeding is currently well-established, it may be that mitigation measures focussed on human health, by emphasising safer handling of products in the home, will have the most significant impact in the short- to medium term.

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Conflict of interest

No conflicts of interest have been declared.

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