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Food Microbiology Reference Tool

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Targets of Irradiation – What are they and how do we kill or inactivate them?

Understanding the differences between the agents of illness and spoilage can help to understand how or if irradiation can kill or inactivate them.

Most spoilage or pathogenic (harmful) agents in foods are microorganisms, which are commonly considered to be bacteria, yeasts and molds. Other harmful agents include insect pests, parasites, prions and viruses. The FDA has an online reference book for pathogenic microorganisms and parasites at:
http://vm.cfsan.fda.gov/~mow/intro.html

Bacteria – Small single cells of various shapes. Bacteria replicate the same way (replicate the cell's genetic matter and then divide the cell in two). Consequently, if irradiation harms the cell structure or genetic material, the process can kill the bacterial cell. Bacteria are also sensitive to their environment, so chemical changes caused by irradiation can damage or kill them. Some bacteria can form tough dormant spores in response to hostile environments and these spores are very difficult to kill with irradiation or other means. Bacteria are classified by their acceptance of Gram stain. Gram-positive bacteria are often slightly more likely to tolerate irradiation, but you can't definitely rely on this to tell you the bacteria's response to radiation.

Fungi - Fungi include molds and yeasts. Usually more difficult to kill than bacteria because of their shape, growth characteristics and adapability.

> Molds – Fast growing multicellular fungi of various shapes, but mostly stringy. They multiply in many different ways. Under a microscope, molds look like various forms of sea coral. They are often stringy and if a piece is broken by irradiation, the broken piece is often still capable of growth. This is one reason they are difficult to kill. Molds are the most tolerant micrororganism to changes in pH, water content and oxygen, so the environmental changes caused by irradiation may not affect them as much.
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> Yeasts – Single cell fungi, but some have stringy parts. The cells are larger than bacteria and of various shapes. Can replicate in different ways, making them somewhat more difficult to kill than bacteria. Yeasts that survive irradiation can sometimes grow very quickly, resulting in quick spoilage of some irradiated foods.

Insect pests – I use this term to include insects, spiders and the other small creatures that have various life stages and are sometimes living in or hitchhiking in food. They can carry disease, but often are not actually harmful if eaten (unless you see them!). The problem is they can be harmful to agriculture and spoil food with their excrement, webs and living structures. Insect pests damage food quality and are generally distasteful. Insect pests vary in their sensitivity to radiation depending on the life stage. Rapid growth stages are usually less tolerant to radiation. So, usually, eggs are more sensitive than are larvae; following larvae, the pupae (cocoons) are more sensitive and finally adults are very difficult to kill, but easy to sterilize.

Parasites – Small animals that live their lives in other animal hosts. They are much larger than bacteria or fungi (if you apply a stain to the food you can often see them, even without magnification), and have several life stages (egg, larvae, adult). They may develop in foods, but unlike bacteria, parasites do not proliferate in foods. They are often easier to kill because they are sensitive to their environment and if one life stage is damaged, it might not be able to proceed to the next life stage. It is less difficult to characterize the radiation tolerance of parasites, in part because much less research has been done on them.

Prions - extremely small protein-like fractions that, like viruses, are not alive. Prions are considered to be the infective agent for Transmissible Spongiform Encephalophies (TSE) such as Scrapie (a disease of sheep) and 'Mad Cow' disease, the Bovine form of the disease, shortformed as BSE. I have seen nothing that would indicate prions could be inactivated by irradiation at any reasonable dose.

Viruses – protein-protected DNA or RNA, these agents use their hosts's biological components to create havoc, but viruses are not actually alive. Therefore we don't kill viruses, we inactivate them. Since protein is not much affected by irradiation (and the proteins around viruses are tough), irradiation has to directly hit the DNA or RNA and break it to inactivate a virus. This is one reason why inactivating viruses usually requires a higher dose than killing bacteria. Viruses vary in their sensitivity to environment so chemical change may or may not inactivate them. They are usually quite heat sensitive. Although high coliform counts are usually a good indicator of bacterial contamination, it isn't true with viruses. So, shellfish taken from water with low coliform counts can still be quite contaminated with viruses.

Common Foodborne Spoilage Bacteria - Quick Notes

Coliform – Gram-negative. A collective name for several members of the Enterobacteracae family that includes some pathogens and some indicators of spoilage. Generally a coliform measurement is an indicator of fecal contamination, and not necessarily an indication of the presence of pathgens. Coliforms are everywhere, including probably all foods. Therefore, we shouldn't confuse a coliform count with the presence (or not) of E. coli, which is part of the same family but a different species.

Lactobacillus – Gram-positive. Similar to *Leuconostoc*. Spoilage organisms found everywhere but mostly found in plant products and dairy products, and also can spoil processed meat products. Acid and cold tolerant.

Leuconostoc – a Gram-positive spoilage bacterium most commonly found in plant products. Also implicated in spoilage of fresh milk and dairy, fresh refrigerated dough products and raw and processed meats (will grow in vac-packed and MAP meats and dough even at refrig temps). Similar to *Lactobacillus*, this bacteria is a lactic acid generator. This species is commonly used as starter cultures in dairy processing, and also some fermented beverages because it generates ethanol.

Pseudomonas – Gram-negative. By far the most important refrigerated food spoilage organisms. Also commonly implicated in contamination of cosmetics where they can cause skin and eye illnesses.

Common Foodborne Pathogenic Bacteria - Quick Notes

Bacillus species - Gram-positive sporeformers. The need for and difficulty of killing *Bacillus* species spores are one of the reasons that dry foods and ingredients have to be irradiated at higher doses.

> *Bacillus cereus* –pathogen of rice, spices, flour, dry soup mixes. This bacteria usually causes illness by producing a toxin that is consumed in reheated or inadequately heated foods. For example, the spore found in rice will usually not cause illness if the rice is eaten immediately after cooking. But if you take the cooked rice and stuff a turkey, or leave the rice at warm temperatures, illness can easily result.
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> *Bacillus subtilis* – Gram positive sporeformer. Originates in soil; causes spoilage of organism of cereals and flour and herbs and spices. *B. subtilis* in spices and soup mixes has been implicated in foodborne illness (once the spores are activated by heat and being placed in moist foods, they germinate, a toxin is produced which cause illness when the leftovers are eaten).

Campylobacter – Gram-negative. (Pronounced Camp - e - lobacter). A pathogen of meat origin and found on most meat carcasses of all species. Even though it is quite heat and freezing sensitive it is considered to cause more illness than any other pathogen, but it is either reported less or lab tests were insufficient to correctly label it. Although the best known pathogen in this species is *Campylobacter jejuni*, several other Campylobacters also cause illness. Campybacteriosis is considered a mild illness, but it has been found to sometimes cause Guillume Barre syndrome a very serious and long term neurological disability.

Clostridium – Gram-positive sporeformers, heat tolerant, grows only in low oxygen situations, but low oxygen situations can be found in surprising places, such as under mold or deep in muscle tissue. Species includes several pathogens. Of soil and water origin they are also important pathogens of meat. Illness is caused by the toxins produced by Clostridium species.

> *Clostridium botulinum* – Forms heat and radiation resistant spore; vegetative cells produce toxin. Probably the most difficult bacteria to kill and, if the food allows the growth of this organism, it is the most important organism to kill. Causes one of the most serious forms of foodborne illness -botulism.
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> *Clostridium perfringens* – Heat resistant sporeformer; vegetative cells produce toxin. Found in soils, foods are also commonly contaminated with this microorganism by humans. Found in spices, meats and poultry and meat gravies. Causes diarrhea with severe pain.

E. coli – Gram negative. (The E. stands for *Escherichia* which is hard to pronounce so no one does.) These bacteria cause illness by producing toxins, but unlike *Bacillus*, *Clostridium* or *Staph* species, the toxin in not formed in the food. *E. coli* toxins are formed inside the person who ate the bacteria. Some cause severe gastro-intestinal illness, and one serotype 0157:H7 causes kidney damage, organ breakdown and sometimes death.

Listeria – Gram positive. One of the more common food pathogens, *Listeria monocytogenes* is increasingly implicated in illness from refrigerated foods. *Listeria* is one of the more radiation resistant food-borne pathogens, especially at lower temperatures. Although healthy adults may not become ill from Listeria, the fatality rate for persons who become ill from Listeria is high, (about 34% from illness studied in the 1980's). Listeriosis of pregnant women can cause fetal death and stillborne births.

Salmonella – Gram-negative. Several *Salmonella* serovars cause illness. Very widely distributed, especially in animals or animal products (such as milk and eggs). Ingestion of *Salmonella* causes serious illness and can cause particularly disabling forms of arthritis. Salmonellosis is the most common reported foodborne illness in the United States.

Shigella – Gram-negative. Three *Shigella* species are foodborne, but essentially they all cause illness from human contamination of food. Similarly to *E. coli, Shigella* forms a toxin inside whoever consumes it. Since it causes a serious illness, it is often reported to health authorities. It is the third most reported foodborne illness.

Staphylococcus aureus – Gram positive, toxin producer. Several *Staph* species also cause foodborne illness, but this one is the more dangerous and well known foodborne disease agent. (Note: *Staph* also contaminate cosmetics, medical supplies etc.) Food contamination by this microorganism is virtually always because of human contamination. When this bacteria is allowed to grow in foods, usually after human contamination and improper holding temperatures, it can produce a toxin. Tests that measure the presence of coagulase-positive *Staph* are used to indicate the likely presence of *Staph aureus*. Generally, finding even low counts of *Staph. aureus* in prepared foods might mean that irradiation should not be used since it will not destroy the toxin that can cause illness and could kill the spoilage organisms that might otherwise cause the food to be thrown out. A finding of Staph aureus in a food presented for irradiation requires a lot of information about the food, its processing and storage history before accepting it for irradiation.

Vibrio – Gram-negative and very fast growing even at cold temperatures. Three *Vibrio* species are food or water pathogens. *Vibrio cholerae* is water borne, but V. parahaemolyticus and V. vulnificans come from seafood. Foodborne illness from *Vibrio* can be very serious/deadly.

Yersinia – Gram-negative toxin producer. The toxin is heat-stable, meaning this bacteria has to be quickly killed before it can develop toxin. Some are pathogens and one, *Y. pestis* is famous for causing the Plague. Food sources of *Y. enterocolitica* are usually animals, especially pigs, and raw milk, but *Yersinia* have also been found in fresh water fish or fowl, seafood, vac-packed meats.

Common Foodborne Fungi - Quick Notes

Fungi usually cause spoilage, but some can also cause illness either directly, or because they produce toxins.

Aspergillus (mold) – responsible for black rot of several fruit, spoilage of ham and bacon and oils. While some are commercially used to make fermented foods, some of these fungi produce powerful toxins. The toxins are not radiation sensitive.

Botrytis (mold) – grey or blue mold on fruit such as apples, pears, berries and citrus.

Fusarium (mold) – common soil contaminant causes brown rot of fruit, and rots of wheat and barley. An inhalant danger.

Saccharomyces (yeast). More commonly used commercially for fermentation of been wine, Champagne etc. Some of them do spoil juice, juice concentrates, salad dressings and wine. When acting as spoilage organisms, they usually act in concert with *Lactobacillus* bacteria.

Common Foodborne Parasites – Quick Notes

Guiardia – Mostly waterborne. Guiardia can infect food through contamination with animal feces or contaminated water. Hikers and campers who are tricked into thinking cool mountain streams contain pure water can be infected with this parasite.

Cryptosporidium parvum – Pet reptiles are a frequent source of this parasite, but human or animal feces used as fertilizer has resulted in numerous cases from contaminated berries. Healthy adults may not become sick but this parasite is a serious infection for AIDS patients and other immunocompromised persons. Even healthy individuals have been known to produce 17 liters of stools in one day with the diarrhea that this parasite causes!

Toxoplasma gondii – Pet cats are the most frequent source of this parasite, but it is also found in meat. Adults may contract the parasite with no symptoms (usually by eating undercooked meat), but it also causes severe illness/deaths of human fetuses.

Trichinella spiralis **–** Raw or undercooked pork is the usual source of this parasite, but hunters consuming inadequately cooked bear meat have also contracted the disease – Trichinosis. Trichinosis rarely kills it victims – but as the parasite burrows into their muscles, its victims probably wish it did!

Also note there many other parasites associated with fish and seafood that are not covered here; most cause spoilage and economic damage.

Foodborne Viruses – Quick Notes

Hepatitis A. - This is a virus of family Picornaviridae, a piece of information that is important only because it tells us this virus is in the same family as polio, Echovirus and Coxsackie virus (and because there has been irradiation research done on the radiation resistance of these viruses). They are single stranded RNA genomes, (not DNA virus like Smallpox). Hep A is usually a human health concern when infected individuals contaminate food. It has also been found to infect shellfish, fruits and vegetables when contaminated by feces.

Norwalk and related viruses – Waterborne and foodborne, Norwalk is usually implicated in large outbreaks and often in social setting involving children or older adults (camps, day care, holiday cruises etc.). Since it is usually caused by human contamination of foods that are then served without further cooking, it does not seem that irradiation has a part to play in prevention of Norwalk. I'm including it because it is becoming better known and you might be asked about it.

(Note: There are many known viruses, and probably many more that have not been well studied that are not included here.)

How to Use the D_{10} Value Table

For our purposes, a D_{10} value is the amount of radiation required to kill 90% (one log) of the microorganism.

However, killing 90% of them is usually not enough. Depending on the common bioburden, or the perceived need for treatment, or the claim (e.g. pasteurization), you may want to target three or five times the treatment. This is called a $3D_{10}$ or a $5D_{10}$ treatment. Sterilization is generally considered to occur if a $12D_{10}$ treatment for *Clostridium botulinum* is achieved.

A table of D_{10} values can be misleading. As with other research, published D_{10} values are sometimes very reliable and sometimes less reliable. Therefore, the results could be considered a likely estimate, or if the research has been replicated by several researchers and where the effect of different methods has been examined, the D_{10} value may be exact. Much of the D10 research has been conducted with laboratory strains, instead of naturally occurring strains. Naturally occurring strains can sometimes be more adapted and difficult to kill. For this reason, a published D_{10} value cannot always tell you the radiation dose to kill that microorganism even when all the conditions might be the same. When conditions are different (eg. temperature, food type, pH, salt or water content, atmosphere), the D_{10} value could be quite different.

Therefore when assisting customers to prepare HACCP plans or to plan confirmatory research, use the table of D_{10} values to target and bracket the likely minimum dose.

One of the problems with relying just on D_{10} values when trying to understand what the microbiological effect is that most of the research does not report the results in D_{10} values. Consequently, a table of D_{10} values only gives us about one-third of the research that might have been done with that food and that microorganism.

Generally, selecting a correct dose for processing requires the following pre-requisite knowledge:

- The type and usual bioburden of the microorganisms present (or potentially present),
- The regulated tolerance level for the microorganism, or if there is no regulatory guidance, it would be helpful to know other risk assessment factors such as the group most likely affected by the pathogen (children? Pregnant women? etc), or the human-infective dose of the microorganism, if possible,
- The D_{10} of the most resistant or target microorganism in the product to be treated, under the conditions of processing to be used (Refrigerated?, Frozen?, Heat treated?, Type of packaging?).

Gathering information on the potential microbial hazards of the product, such as D_{10} values, and knowledge of the regulated tolerance levels or risk of the microorganism, is part of hazard analysis under HACCP.

Summary Table of D_{10} Values from Published Research
(alphabetical by microorganism)

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Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Achromobacter xylooxydans	Frozen shrimp	0.052	Charbonneau et al, 1986
Acinetobacter calcoaceticus (catalase +) (psychrotroph) (catalase -)	Frozen shrimp	 0.084 0.106 0.108	Charbonneau et al, 1986
Aeromonas hydrophila (five isolates)	2°C blue fish or ground beef 15° blue fish or ground beef	0.14-0.19 0.22-0.34	Palumbo et al, 1986 in Thayer 1992
Aeromonas hydrophila	Frozen shrimp	0.038	Charbonneau et al, 1986
Agrobacterium rachobacter (psychrotroph)	Frozen shrimp	0.067	Charbonneau et al, 1986
Alcaligenes faecalis	Frozen shrimp	0.066	Charbonneau et al, 1986
Arcobacter butzleri (ATCC 49616)	Ground pork, in vacuum, on ice	0.27±4.8%	Grass prawns (Penaeus monodon) -10±2°C
Aspergillis sp (fungi)	Mangoes and Bananas	0.25	Alabastro et al, 1978
Aspergillis flavus (var. columnaris, several strains) *petrikii* *flavus* *parasiticus*	Spices, (range gives first wet and then dry conditions)	 0.26-0.60 0.32-0.65 0/30-0.57 0.37-0.56	Kume et al, 1989

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Bacillus spp *(non-pigment psychrotroph)* *(pigmented psychrotroph)*	Frozen shrimp	 0.088 0.166	Charbonneau et al, 1986
Bacillus cereus	3-4°C, Cooked cauliflower and potatoes	 0.12-0.28	Grant and Patterson, 1992
Bacillus cereus (stationary cells)	5°C, in vacuum or in air Mechanically deboned chicken	 0.45±0.02	Thayer and Boyd, 1994
Bacillus cereus (endospores)	5°C Mechanically deboned chicken Beef round Pork loin Turkey breast Beef gravy	 1.92+0.072 2.78+0.173 2.78+0.315 1.90+0.113 2.77+0.205	Thayer and Boyd, 1994
Bacillus cereus (endospores)	5°C, in vacuum or in air Beef or pork	 2.78	Thayer and Boyd, 1994
Bacillus cereus	5°C in air and in vacuum Mechanically deboned chicken Logarithmic cells Stationary cells Endospores	 0.18±0.008 0.43±0.016 2.56±0.21	Thayer and Boyd, 1994
Bacillus coli	Frozen liquid egg	0.258	Fengmei et al, 2000
Bacteria (unspecified, and method unspecified)	Ground black pepper Paprika Thyme Marjoram Spice mix for goulash Spice mix for Frankfurters Spice mix for RTE pork sausage Spice mix for boiling sausages Mustard powder Curry powder	1.9 1.7 1.8 1.8 1.7 2.1 1.5 1.6 1.6 1.3	Wetzel et al, 1985

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Bacteria (aerobes)	Powdered red pepper - e-beam Powdered red pepper - gamma Powdered ginger – e-beam Powdered ginger - gamma	1.5 1.6-1.8 1.3-2.2 1.4-2.7	Lee et al, 2000
Bacteria *(unspecified, Total Viable Plate Count method)*	Coriander Cumin Turmeric Chili	2.14 1.67 1.67 1.07	Alam et al, 1992
Bacteria *(unspecified, Total Plate Count method)*	Turmeric Black Pepper Chili	1.44 1.53 1.25	Lokendra Singh et al, 1988
Bacteria (unspecified, Total Plate Count method)	White pepper Paprika Nutmeg	1.77 1.88 2.14-2.38	Calenberg et al, 1998
Bacteria (mesophiles, Standard Plate Count method)	Paprika	2.12-2.14	Nieto-Sandoval et al, 2000
Bacteria (aerobes)	Paprika Whole Black Pepper	1.44 1.29	Kiss and Farkas, 1981
Byssochlamys fulva (mold)(ascospores, three strains)	Sterilized apple juice, 25°C	1.2	Van der Reit and Van der Walt, 1985
Campylobacter jujuni	Ground beef, 3-5°C, 8-14% fat Ground beef, -17-15°C, 8-14% fat Gound beef, 3-5°C, 27-28% fat Ground beef, –17-15°C, 27-28% fat	0.17±.005 0.23±.017 0.19±.017 0.20±0.16	Clavero et al, 1993
Campylobacter jujuni (three strains)	Raw beef, 18-20°C	0.14-0.16	Tarkowski et al, 1984

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Campylobacter *jejuni* NCTC 11351 *jejuni* FN1 *jejuni* FN2 *coli* FM3 *coli* NCTC 11366 coli FM4 *fetus* NCTC 10842 *lari* NCTC 11352	Minced chicken, sterilized and then inoculated, 4°C	 0.19 0.16 0.13 0.25 0.14 0.12 0.14 0.14	Patterson, 1995
Campylobacter jujuni	Ground pork, in vacuum, on ice	0.19±4.2%	Collins et al, 1996
Clostridia (Sulfide-reducing type)	Paprika	3.84-4.65	Nieto-Sandoval et al, 2000
Clostridium botulinum, Types A, B	Cured bacon, in vacuum, in cans	2.20 – 2.39	Anellis et al 1965, reported in Thayer 1986
Clostridium botulinum, Types A, B	Cured ham, cooked, in vacuum, in cans, -30°C	2.6	Anellis et al 1977a, reported in Thayer 1986
Clostridium botulinum, Types A, B	Corned beef; pork sausage, in vacuum, -30°C ±10°C	1.9 – 2.14	Anellis et al 1962, reported in Thayer 1986
Clostridium botulinum, Types A, B	Cooked, in vacuum, in cans, -30+10°C beef chicken pork loin	 3.4 3.5 3.6	Anellis et al 1969, 1977b, 1979, reported in Thayer 1986
Clostridium botulinum, Types A,B	Cooked, in vacuum, in cans Pork Chicken	 3.64 3.58	Anellis et al, 1977b

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Clostridium perfringens (vegetative cells)	3-4°C Cooked minced beef	 0.34-0.58	Grant and Patterson, 1992
Clostridium perfringens	Intestines used as natural sausage casings Small fresh pork casings Large fresh pork casings	 5.68 5.07	Trigo and Fraqueza, undated
***Clostridium perfringens (range of two substrate and plating methods)*	Cooked Roast beef Gravy Cauliflower Roast potatoes Mashed potatoes	 0.79-0.58 0.36-0.41 0.47-0.52 0.42-0.48 0.34	Grant and Patterson, 1992
Clostridium perfringens	Ground pork, approx 4°C, summary of two plating methods In air 25%CO_2:75%N_2	 0.79-0.826 0.67-0.75	Grant and Patterson, 1991
Clostridium sporogenes (ATCC 7955)	Chicken breast, in vacuum, on ice D10 for irradiation alone D10 for irradiation when proceeded by 6,800 atm at 80°C for 20 min	 4.1 2.0	Crawford et al, 1996
Coliforms (unspecified)	Turmeric Black pepper Chili	1.04 0.96 1.0	Lokendra Singh et al, 1988
Coliforms (unspecified)	Coriander Cumin Turmeric Chili	0.36 0.63 0.42 0.71	Alam et al, 1992
Coliforms (unspecified)	Paprika	3.15-3.25	Nieto-Sandoval et al, 2000
Colletotrichum sp (fungi)	Mangoes and bananas	0.54	Alabastro et al, 1978
Coxsackie virus	Water Media Cooked frozen ground beef	1.2 4.8 8.1	Jacobs, 1994

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Enterobacteriacae	Intestines used as natural sausage casings Small fresh pork casings Large fresh pork casings Beef dry casings	 0.27 0.33 1.48	Trigo and Fraqueza, undated
Enterobacteriacae	Paprika	2.66-3.02	Nieto-Sandoval et al, 2000
E. coli	Grass prawns (Penaeus monodon) -10±2°C	0.39	Hau et al, 1992
E. coli (two plating mediums, summary results	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.35-0.38 0.28-0.29 0.26-0.27 0.23-0.25	Patterson, 1988
E. coli	Ground pork, approx 4°C, summary of two plating methods In air 25%CO_2:75%N_2	 0.33-0.34	Grant and Patterson, 1991
E. coli	5°C Beef Lamb Pork Turkey breast Turkey leg	 0.30 ±0.02 0.32±0.02 0.30±0.01 0.30±0.01 0.29±0.04	Thayer et al, 1995
E. coli 0157:H7	In vacumm, 5°C Finely ground lean beef Lean ground beef (2.6% fat) Mechanically separated chicken (21.3% fat)	 0.28 0.27 0.27	Thayer and Boyd, 1993
E. coli 0157:H7 (three strains, non-acid adapted and acid adapted cells)	Pasteurized, clairified apple juice	0.12-0.31	Buchanan et al, 1998

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
E. coli 0157:H7	Ground beef, 3-5°C, 8-14% fat Ground beef, -17-15°C, 8-14% fat Gound beef, 3-5°C, 27-28% fat Ground beef, –17-15°C, 27-28% fat	0.24±.012 0.30±.015 0.25±.028 0.30±0.23	Clavero et al, 1993
Echovirus	Water Media	1.4 5.7	Jacobs, 1994
Hepatitis A virus	Artificially inoculated fruits and vegetables, room temperature	2.7 – 3.0	Jacobs, 1994; Bidawid et al, 2000
Hepatitus A virus	Clams, Oysters (live, 4°C, in air), numerous assay methods, (summary results, paper should be reviewed before research is started)	2.02	Mallett et al, 1991
Hepatitus A virus	Lettuce ambient temp Strawberries ambient temp	2.72±0.05 2.97±0.18	Bidawid, et al, 2000
Lactobacillus	Shrimp (On ice, likely 1±1°C)	0.59	Angel, 1986
Lactobacillus spp	Frozen shrimp	0.102	Charbonneau et al, 1986
Lactobacillus spp	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.59 0.40 0.50 0.51	Patterson, 1988
Listeria moncytogenes	5°C Beef Lamb Pork Turkey breast Turkey leg	 0.45±0.03 0.47±0.04 0.48±0.02 0.50±0.03 0.47±0.03	Thayer et al, 1995

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Listeria monocytogenes (strain ATCC 35152)	Boneless chicken and minced lamb, in air, 0°C and 5°C	0.5	Kamat and Nair, 1995
Listeria monocytogenes (two strains, summary results)	Ground pork, approx 4°C, summary of two plating methods In air 25%CO_2:75%N_2	 0.51-0.64 0.51-0.70	Grant and Patterson, 1991
Listeria monocytogenes	White crab meat 4°C	0.59	Chen et al, 1996
Listeria monocytogenes	Beef (tenderloin) 0° -5°C -20°C	 0.45 0.77 1.21	Thayer and Boyd, 1995
Listeria monocytogenes	Chicken meat	O.43	Huntanen et al, 1989 in Thayer et al 1995
Listeria monocytogenes	Chicken meat, ground	0.41-0.55	Patterson, 1988 in Thayer et al, 1995
Listeria monocytogenes	Ground beef	0.51-0.61	Beuchat et al, 1993 in Thayer et al, 1995
Listeria monocytogenes	3-4°C Cooked ground beef and cooked cauliflower and potatoes	 0.30-0.64	Grant and Patterson, 1992
Listeria monocytogenes	4 $\pm$1°C beef bologna 3.5% soy protein beef bologna 1.75% soy protein beef bologna 0% soy protein	 0.66 0.68 0.71	Sommers et al 2001
Listeria monocytogenes	Ground beef, 3-5°C, 8-14% fat Ground beef, -17-15°C, 8-14% fat Gound beef, 3-5°C, 27-28% fat Ground beef, –17-15°C, 27-28% fat	0.58+.063 0.61+.045 0.57+.039 0.57+.030	Monk et al, 1994

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Listeria monocytogenes	4+1°C Beef frankfurters (product 1) Beef frankfurters (product 2) Mixed meat frank (product 1) Mixed meat frank (product 2) Poultry frank (product 1) Poultry frank (product 2) Poultry frank (product 3)	 0.52±0.09 0.52±0.09 0.71±0.09 0.71±0.07 0.49±0.12 0.70±0.09 0.64±0.11	Sommers and Thayer, 2000
Listeria monocytogenes (ATC19111)	Sterilized chicken meat, on ice (summary of three dose rates)	0.36-0.38	Dion et al, 1994
Listeria monocytogenes	Shrimp, previously radiation sterilized and then artificially contaminated FDA-1A1 stationary phase 0°C FDA-1A1 stationary phase –20°C ATCC 19115 stationary phase 0°C ATCC 19115 stationary phase –20°C	 0.27-0.28 0.67-0.74 0.34-0.36 0.81-0.84	Brandao-Areal, et al, 1995
Micrococcus spp	Frozen shrimp	0.509	Charbonneau et al, 1986
Mold (unspecified)	Coriander Cumin Turmeric Chili	2.14 1.25 0.83 0.71	Alam et al, 1992
Molds and yeasts (unspecified)	Paprika	3.36-3.86	Nieto-Sandoval et al, 2000
Moraxella spp (MacConkey – psychrotroph) (MacConkey + psychrotroph)	Frozen shrimp	 0.379 0.426	Charbonneau et al, 1986

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Moraxella phenylpyuvica	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.85 0.67 0.62 0.88	Patterson, 1988
Polio virus	Water Media	1.1 5.4	Jacobs, 1994
Polio virus	Clams, Oysters (live, 4°C, in air), numerous assay methods, (summary results, paper should be reviewed before research is started)	3.1	Mallett et al, 1991
Pseudomonas putrafaciens (catalase –) *aeruginosa* (psychrotroph) *paucimobilis* spp catalase -	Frozen shrimp	 0.028 0.036 0.037 0.091	Charbonneau et al, 1986
Pseudomonas putida	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.08 0.110 0.06 0.08	Patterson, 1988
Rotavirus	Clams, Oysters (live, 4°C, in air), numerous assay methods, (summary results, paper should be reviewed before research is started)	2.4	Mallett et al, 1991

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Salmonella spp	5°C Beef Lamb Pork Turkey breast Turkey leg	 0.70±0.04 0.67±0.04 0.51±0.03 0.71±0.04 0.71±0.04	Thayer et al, 1995
Salmonella	Ground beef, 3-5°C, 8-14% fat Ground beef, -17-15°C, 8-14% fat Gound beef, 3-5°C, 27-28% fat Ground beef, –17-15°C, 27-28% fat	0.62±.089 0.80±.054 0.66±.031 0.74±.057	Beuchat et al, 1993
Salmonella spp	5°C Bison Ostrich Alligator Caiman	 0.55±0.03 0.50±0.01 0.54±0.02 0.53±0.04	Thayer et al, 1997
Salmonella	Egg powder	1.0	Narvaiz et al, 1992
Salmonella *anatum* *arizonae* *newport* *enteritidis* *enteritidis* *newport* *typhimurium* *typhimurium*	In air and in vacuum, 4°C Mechanically deboned chicken Meat	 0.52±0.114 0.44±0.057 0.53±0.107 0.56±0.095 0.77±0.095 0.37±0.030 0.39±0.010 0.51±0.034	Thayer et al, 1990
Salmonella enteritidis	Orange juice (five formulations including calcium added)	0.35-0.37	Niemira, 2001
Salmonella enteritidis	Grass prawns (Penaeus monodon) -10±2°C	0.48	Hau, 1992
Salmonella (mixtures of *S. lille, S. enteritidis* and *S. typhimurium*)	Egg powder	0.8	Matic et al, 1990.

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Salmonella typhimurium (strain SR-11) (strain RIA)	Sterilized chicken, 4°C	 0.52 0.66	Previte et al, 1970
Salmonella typhimurium; *Salmonella stanley*	18-20°C Raw ground beef	0.55 0.78	Tarkowski et al 1984 in Thayer et al, 1995
Salmonella typhimurium (two media methods, summary results)	Minced chicken, sterilized then inoculated, 4°C In air CO_2 N_2	 0.43-0.50 0.44-0.54 0.55-0.62	Patterson, 1988
Salmonella typhimurium (two strains, summary results)	Ground pork, approx 4°C, summary of two plating methods In air 25%CO_2:75%N_2	 0.41-0.86 0.37-0.92	Grant and Patterson, 1991
Salmonella typhimurium (two strains)	In air, 10°C Pork	0.40 – 0.86	Patterson 1991 in Thayer et al, 1995
Salmonella typhimurium	Soft shell clams (probably room temperature)	0.58-0.64	Licciardello et al, 1989
Salmonella typhimurium	3-4°C Cooked minced beef	 0.37-0.69	Grant and Patterson, 1992
Salmonella *typhimurium* *panama* *anatum* *Stanley*	Raw beef, 18-20°C	 0.55 0.66 0.67 0.78	Tarkowski et al, 1984
Salmonella typhimuium (ATCC 14028)	Sterilized chicken meat, on ice (summary of three dose rates)	0.31-0.33	Dion et al, 1994

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Shigella flexneri	Soft shell clams (probably room temperature	0.30-0.35	Licciardello et al, 1989
Staphylococcus spp	Frozen shrimp	1.121	Charbonneau et al, 1986
Staph. aureus	5°C beef lamb pork turkey breast turkey leg mechanically deboned chicken	 0.46±0.02 0.40±0.03 0.43±0.02 0.45±0.03 0.45±0.05 0.41±0.03	Thayer et al, 1995
Staph. aureus	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.41 0.41 0.39 0.37	Patterson, 1988
Staph. aureus	Grass prawns (Penaeus monodon) -10±2°C	0.029	Hau et al, 1992
Staph. aureus	White crab meat 4°C	0.16	Chen et al, 1986
Staph. aureus	5°C Bison Ostrich Alligator Caiman	 0.40±0.02 0.34±0.02 0.36±0.01 0.38±0.01	Thayer et al, 1997
Staph. aureus (strain ATCC 13565)	Sterilized, mechanically deboned chicken, 0°C Stationary phase cells, combined results of in vacuum and in air Mid-log phase cells in vacuum	 0.36±0.01 0.27±0.02	Thayer and Boyd, 1992
Staph. aureus	Various atmospheres Chicken mince	 0.37-0.42	Patterson, 1988, in Thayer et al, 1995
Staph. aureus	Low fat beef High fat beef	0.58 0.30	Maxcy and Tiwari, 1973 in Thayer et al, 1995

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Staph. aureus	Ground beef, 3-5°C, 8-14% fat Ground beef, -17-15°C, 8-14% fat Gound beef, 3-5°C, 27-28% fat Ground beef, –17-15°C, 27-28% fat	0.45±.035 0/45±.038 0.44±.022 0.43±0.47	Monk et al, 1994
Staph. aureus	Soft shell clams	0.80-0.89	Licciardello et al, 1989
Streptococci spp	Frozen shrimp	0.137	Charbonneau et al, 1986
Streptococci (faecal origin)	Intestines used as natural sausage casings Small fresh pork casings Large fresh pork casings Beef dry casings	 1.25 2.24 5.53	Trigo and Fraqueza, undated
Streptococcus faecalis	Soft shell clams (probably room temperature)	0.97-1.10	Licciardello et al, 1989
Streptococcus faecalis	Minced chicken, sterilized then inoculated, 4°C In air CO_2 In vacuum N_2	 0.65 0.70 0.69 0.67	Patterson, 1988
Vibrio spp	White crab meat	<0.10	Chen et al, 1996
Vibrio cholera	Grass prawns (Penaeus monodon) -10±2°C	0.11	Hau et al, 1992

Microorganism or infective agent	**Food source and environmental conditions**	**D_{10} (kGy)**	**Reference**
Vibrio parahaemolyticus	Frozen shrimp	0.10	Bandekar et al, 1987
Vibrio vulnificans	Shellstock oysters (oysters in shell) Virulent form Avirulent form	 0.062 0.037	Dixon et al, 1995
Yeasts and molds (unspecified)	Turmeric Black pepper Chili	1.23 1.14 1.21	Lokendra Singh et al, 1988
Yersinia enterocolitica	Beef, 25°C	0.11	El-Zawahry and Rowley, 1979 in Olson 1998
Yersinia enterocolitica (three strains)	Raw beef, 18-20°C	0.10-0.21	Tarkowski et al, 1984
Yersinia enterocolitica (NCIMB 11174)	Ground pork, approx 4°C, summary of two plating methods In air 25%CO_2:75%N_2	 0.16 0.17-0.18	Grant and Patterson, 1991
Yersinia enterocolitica (strain F5692)	Homogenate of raw meat and salami 0-5°C -40°C	 0.25 0.25	Kamat et al, 1997

Notes:

Where possible, D_{10} values determined when the microorganism was in food were preferentially selected for reporting in this table. Usually D_{10} measurements in media were omitted.

Although the correct abbreviation is S. for both *Staphylococcus* and/or *Salmonella*, for the purposes oyf this table I have used the abbreviation Staph. to prevent confusion.

Where $12D_{10}$ values were reported by published authors, these were recalculated to give a D_{10} value. According to Dr. Don Thayer, this gives us a fairly close D_{10} value but since $12D_{10}$ values have to include a shoulder for the kill curve for *C. botulinum*, it may be a bit high.

** Grant and Patterson noted several differences in D_{10} values of *C. perfringens* when different microbiological methods were used. The range in this table reflects both methods; the standard error was omitted since it was reflected in the range.

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