Cold chain management in meat storage, distribution and retail: A review

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Abstract. Meat is a perishable product with a short shelf life and therefore short selling times. Therefore, cold chain management in meat supply is of utmost importance for the maintenance of quality and safety of meat/meat products. Raw meat/meat products are likely to support the growth of pathogenic microorganisms and/or spoilage bacteria, and should be kept at temperatures that do not result in a risk to health. The cold chain should not be interrupted at all times along the meat distribution chain. The complexity of global meat supply chain, with frequently long distribution chains associated with transportation of the product within one country, from one to another country and from one to another continent, makes the solutions for the chilling and freezing regimes, as well as monitoring of time-temperature profiles, very important for the overall success in delivery of product which will be accepted by consumer for its freshness and safety levels. From recently, there are several available options for control and management of the cold chain, such as chilled and frozen storage combinations, superchilling, ionizing radiation, biopreservation, high hydrostatic pressure (HHP), active packaging, wireless sensors, supported with the software-based cold chain database (CCD).

1. Introduction
Meat is a perishable product with a short shelf life and therefore short selling times. In contrast to fresh fruit and vegetables, packaged meat has to be declared with a ‘use by’ date [1]. The maintenance of the cold chain is also one of the main principles and basic requirements of European Union (EU) legislation on food hygiene [2]. Raw materials, ingredients, intermediate products and finished products that are likely to support the growth of pathogenic microorganisms and/or spoilage bacteria, are to be kept at temperatures that do not result in a risk to health. The cold chain should not be interrupted at all times along the meat distribution chain [3].

It is known that shelf life of chilled fresh meat can be extended by various packaging solutions, such as vacuum or modified atmosphere packaging (MAP) [4, 5, 6]. However, a freshness of chilled meat is strongly influenced by temperature. Inadequate storage, distribution and retail temperatures can lead to a significant reduction in shelf life and early spoilage of meat and meat products [6].

Healthy animals that are hygienically slaughtered after proper resting and fasting provide a practically aseptic meat. However, during slaughter, evisceration and dressing operations the microbial cross-contamination usually occurs, especially on the surface of meat, via contact with equipment,
tools, hands, clothes, objects, etc. Meat is a particularly favorable substrate for the growth of microorganisms due to its chemical composition, e.g. rich in proteins, lipids and water. The lipid content of meat also makes it very sensitive to oxidation (the reaction of oxygen with fatty acids) and subsequent production of peroxides. The breakdown products of the peroxides produce the characteristic objectionable odor and flavor of rancid meat.

Several weak points exist in meat cold chain, such as the chilling of products during storage - before shipping, temperature abuse during transport and transferring products from one actor to another and waiting times during consolidation and deconsolidation at retail [7, 8, 9]. Temperature abuses result in variations of product quality during distribution and at the end of shelf life and may cause spoilage before the use by date is reached, leading to food waste and economical losses. The vulnerability of meat cold chain became very important in modern, global meat trade where distribution chain is sometimes very complex and long (slaughterhouse-transportation/distribution-retail-consumer continuum), where meat has to be shipped from one to another country or from one to another continent (Figure 1). Therefore, the management of cold chain is of paramount importance and presents a permanent challenge to maintain the safety and freshness of chilled fresh meat until it reaches the final consumer.

2. Meat spoilage

Pork, beef, lamb and poultry carcasses are chilled immediately after post-mortem inspection at slaughter line and/or in slaughterhouse chilling rooms. The chilling process is aerobic as the carcasses are exposed to air circulation. Most often, after 24-96h of chilling, the carcasses are usually moved to a boning/cutting room where they are further cut into primary cuts (primals). The primals can be typically stored up to 6 weeks in vacuum packs under anaerobic conditions [3]. Ground meat products may be prepared from trimmings from deboning and/or trimmings from primals after 6 weeks of anaerobic storage; these may be stored aerobically or anaerobically (Figure 2).

![Diagram of meat supply cold chain](image-url)
Figure 2. The chilling and chilled storage conditions for beef, pork and lamb carcasses and their primals and trimmings (adapted from [3])

It is well known that chilling of red meat and poultry carcasses is essential to retard bacterial growth. Chilling is also required for appearance and eating quality of meat. Most frequently bovine, pork and lamb carcasses are chilled using a forced convection of chilled air [10], although spray chilling (application of a fine spray) may also be used since it is faster than air chilling and it is primarily used in poultry, but may be also used in beef, pork and lamb processing plants.

According to Regulation (EC) 853/2004/EC the carcasses should be immediately chilled after post-mortem inspection to ensure that the temperature throughout the meat is < 7°C and < 3°C for offal. Interestingly, the provision on time limit by when this temperature must be achieved is not defined. For example, beef and lamb carcasses are usually not chilled to < 10°C (core temperature) within the first 10h to avoid cold shortening and toughening of the meat. Therefore, such conditions are favorable for the bacterial growth on the surface of the carcass, until the temperature is sufficiently reduced to retard bacterial activity [3].

Meat is considered to be spoiled when certain sensory changes occur, e.g. discoloration, off-odor and/or slime development and is usually primarily triggered by spoilage bacteria (Table 1) although indigenous enzymes may also be involved [11]. For instance *Pseudomonads*, *Lactobacillus* and *Enterococcus* produce slime on meat, while *Enterococcus* produce hydrogen peroxide greening spots, similar to greening caused by *Clostridium* spp. The growth of bacteria on meat surface is influenced by temperature, pH, water activity, nutrient availability, storage atmosphere (aerobic or anaerobic) and competition with other microbiota present on meat [12].

Table 1. The overview of the main meat/meat products spoilage defects and causal bacteria (adapted from [8]).

| Defect                  | Meat/Meat product          | Causal bacteria                               |
|-------------------------|----------------------------|-----------------------------------------------|
| Slime                   | Fresh meat                 | *Pseudomonads*, *Lactobacillus*, *Enterococcus*, *Weissella*, *Brochothrix* |
| Hydrogen peroxide greening | Fresh meat               | *Weissella*, *Leuconostoc*, *Enterococcus, Lactobacillus* |
| Hydrogen sulfide production | Cured meats               | *Vibrio, Enterobacteriaceae*                 |
| Sulfide odour           | Vacuum-packed fresh meat   | *Clostridium, Hafnia*                        |
| Cabbage odour           | Bacon                      | *Providencia*                               |
| Cheesy or dairy odour   | Vacuum-packed fresh meat   | *Brochothrix thermosphacta*                 |
| Putrefaction            | Ham                        | *Enterobacteriaceae, Proteus*                |
| Bone taint              | Whole meats                | *Clostridium, Enterococcus*                 |
| Souring                 | Vacuum-packed meats        | *Lactic acid bacteria, Enterococcus, Micrococcus*, |
3. Meat supply cold chain management

Preservation of red and poultry meat for trade and export purposes as anaerobic vacuum-packed product in either chilled or frozen form at sufficiently cold temperatures is essential for successful national and international trade [13]. The impact of long-term chilled storage, as well as frozen storage for export purposes was thoroughly investigated [12, 14]. It was proved that frozen storage durations were extended for more than one year [15]. In spite of these advances, improvement of preservation technologies within the current export cold chain remains an issue, in particular at industrial level, with potential for advancements encompassing superchilling, ionizing radiation, biopreservation and high hydrostatic pressure or high pressure processing (HPP) [16].

3.1. Cold chain in slaughterhouse

In slaughterhouse the meat chill chain starts with two main steps: (a) the primary chilling (rapid cooling of meat carcasses after slaughter) so that the warmest point of the carcass (center of the hind leg) has to reach a temperature of about $< 7^°C / 3^°C$ for edible offal and $< 4^°C$ for poultry carcasses, to prevent microbial growth and extend the shelf life; with current technology these temperatures can be arrived at in 16–24 hours in small carcasses (lamb), in less than 48 hours in large carcasses (beef, pork) and less than 2h for poultry carcasses (internal deep breast); average and surface temperatures are obviously much lower, reaching 0°C on the surface within four hours; this is very important to slow microbial proliferation; and (b) secondary chilling (maintenance of the meat temperature below 7°C (red meat) and below 4°C (poultry meat) at all times during chill storage, cutting, deboning, mincing), before transportation.

The most common technologies to chill meat before transportation are: (i) air chilling, (ii) immersion chilling, (iii) spray chilling, and (iv) vacuum chilling [17].

3.1.1. Air chilling. The effectiveness of air chilling applications depends on a number of factors including air temperature and velocity, relative humidity, weight, fat cover of carcasses and loading of chilling chamber. Air temperature must be within the region of 0°C, with no decrease below -1°C, which could freeze the meat surface and impair its appearance. Air speed can range from 0.25 to 3.0 m/s. However, for economic reasons the most common speeds in use are from 0.75 to 1.5 m/s in the empty section of the cold chamber. Relative humidity during the chilling operation should be kept high to prevent excessive weight loss. The recommended rate is between 90 and 95 %, though this is the most difficult factor to control. It is worth of note that sometimes quick chilling has its problems because of the ‘cold shortening’. Cold shortening can often be seen in beef and mutton, when the meat, still in its pre-rigor phase, reaches temperatures of 10°C or lower. These conditions cause irreversible contractions of the muscle tissue which toughen the meat even after prolonged ripening. Quick primary chilling also signifies an increase in investment and higher operational costs. The chilling period can be reduced by lowering the air temperature (surface freezing risks) or increasing air speed (higher operational costs) or both. Occasionally cold chambers are refrigerated in advance to reach lower temperatures than those in operation (-5°C/-6°C for beef; -10°C/-12°C for pork), taking advantage of thermal inertia to offset the effect of warm meat loads [18].

3.1.2. Immersion chilling. This is the oldest chilling method and also the least expensive method and provides very rapid cooling with no risk of freezing. Immersion chilling is an off-line system that does not allow automatic weighing before and after chilling and is commonly used for the chilling of poultry carcasses, predominantly in USA. Immersion chillers use little floor space and are very energy efficient. The process can be accomplished using just tap water with or without flaked ice or pre-chilled water to create lower temperatures in the immersion bath. Such system is capable of lowering
the temperature of the tap water to 1°C. This process can result in product weight increase by means of a controllable water pick-up. An increase of up to 12% can be achieved.

3.1.3. Spray chilling. This is an alternative method to immersion chilling which has been increasingly used especially in the USA for the chilling of poultry carcasses. Spray chilling can be applied in the processing and production of ‘frozen products’ or ‘hard scalded birds’, as well as ‘fresh products’ or ‘soft scalded birds’. This chilling method is based on combination of sprays and air during the initial stage of the chilling cycle and the use of air for the rest of the chilling period; it uses a cold airflow across the surface of the product and intermittent spraying with cold water. This system prevents the skin from drying out and speeds up the chilling process. With this technique, the discolouration of the skin, which can occur with hard scalded birds, is prevented. Usually, spray chilling tunnels are designed to take one layer of birds in order to prevent cross contamination. Two layers are possible, but the bottom layer must be positioned in between the lines of the top layer to prevent drip contamination and additional drip troughs are required.

3.1.4. Vacuum chilling. This is a rapid batch process whereby moist products containing free water are cooled by evaporation of moisture under vacuum. The advantage of this technology is that it significantly reduces bacterial counts of phychrophiles and mesophiles after the meat was stored for several days. Vacuum packed chilled meat has significantly longer shelf life compared with conventionally chilled wrapped meat. For instance, vacuum packed beef cuts can be stored for up to 12 weeks, while lamb and pork cuts can have a shelf life for up to 5 and 8 weeks, stored at 0°C, respectively. The disadvantage is the large weight loss of meats.

3.2. Cold chain in meat distribution
During meat distribution (transportation) route to the final user - wholesale cold storage and/or display at retail, the cold chain must be maintained vigorously. Industrial and/or truck chambers have different characteristics and performances. Its size, initial temperature of incoming meat, targeted temperature during transportation, mechanical characteristics (e.g. power of compressors, ventilation and insulation), as well as energy/cost matters are issues of first priority when considering the meat distribution/transportation [17]. In general, the vehicle must be provided with a good refrigerated system capable to maintain the required temperature of meat/offal at all times during distribution (see 3.1.).

3.3. Cold chain in meat retail
The maintenance of cold chain during display at retail is of crucial importance for prevention of microbial spoilage, as well as maintenance of meat freshness and safety. The size and capacity of chilling chambers at retail establishment, the size of cabinets, initial temperature of incoming meat, meat handling procedures (cutting, mincing), temperatures of surroundings, location of refrigeration machinery, ventilation and light are the possible weak points to be addressed. The special focus should be put on temperature consolidation/deconsolidation during meat handling (e.g. daily transfer of meat cuts from the chilling chamber to the retail cabinet and vice versa, where internal temperature of meat cuts should be at all times < 7°C). The management approach that dominates in the meat market is related to the principle “First In – First Out”. However, such approach should also adhere to all stages of the cold chain (see Figure 1) and has to be achieved through properly designed handling procedures in the chill storage rooms and retail cabinets. In all, different points of transport, from cold storage in slaughterhouse to retail outlet, and then to consumer refrigerator, are critical points for the overall meat quality and safety.

4. Available options in meat supply cold chain management
As said, if the cold supply chain is breached, meat and poultry products will suffer from a range of quality problems such as shrinkage, rotting, trim loss, unpleasant odor, color and texture changes, as
well as exacerbated health risks from pathogens such as *Salmonella*, *Campylobacter*, Shiga toxin-producing *E. coli* (STEC) and *Listeria monocytogenes*. Despite a numerous studies targeted to better understanding of meat microbial ecology (spoilage microorganisms and food borne pathogens) and its relation to temperature/time within the complex meat supply chain, e.g. meat storage, transportation, distribution and retail, the maintenance of cold chain, as well as meat quality and safety remains a challenge. From recently, there are several options/control measures which can be effectively and synergistically applied to improve the control over the `classic` meat supply cold chain.

4.1. Chilled and frozen storage combinations
Over the previous two decades a numerous studies had been carried out to assess the enhancement of shelf life, as well as quality and safety of meat achieved by chilling and freezing regimes. However, a limited number of studies were conducted to evaluate combined chilled and frozen storage practices, particularly regarding long-term chilled-than-frozen beyond 3-4 months of total duration. It appeared that prolonged vacuum-packed chilled storage (two weeks for beef and lamb, at 4°C and even up to 30 weeks for beef, at -0.5°C and 7 weeks for lamb, at -1.5°C) combined with subsequent frozen storage (up to one year, at -18°C) had the beneficial effect to quality parameters (shear force, tenderness, fluid levels, flavor and color) of meat; the improved tenderness was confirmed as a major achievement [15, 19, 20]. Obviously, the prolonged chilled-frozen storage combinations can have a beneficial effect for export of fresh meat. Further and deeper studies are needed to investigate instrumental color and microbial profile of chilled-then-frozen meat, as these studies are highly relevant for consumer approval and health issues [21].

4.2. Superchilling
Superchilling is used for preserving foods by process in which the temperature of a food product is lowered to 1–2°C below the initial freezing point (for most foods between 0.5°C and 2.8°C). The superchilling technology combines the favorable effect of low temperatures with the conversion of some water into ice, which makes it less available for deteriorative processes. Superchilling gives the food product an internal ice reservoir so that there is no need for external ice around the product during transportation or storage for shorter periods. Generally, superchilling is positioned between freezing and refrigeration (conventional chilling), where the surrounding temperature is set below the initial freezing point. Storing food at superchilling temperature has three major advantages: maintaining food freshness, retaining high food quality and suppressing growth of harmful microbes. It can also reduce the use of freezing/thawing for production and thereby increase yield, reduce energy, labor and transport costs [22].

4.3. Ionizing radiation
Processing of food by ionizing radiation offers arrange of beneficial effects, which can’t be achieved by other and, in particular, traditional techniques such as chilling alone. Food radiation, if applied at low dose (up to 1kGy) can be very effective against parasites presented in red meat, as well as for inactivation of spoilage and pathogen bacteria in chilled and/or frozen meat and poultry. On the other hand, several consumer organizations raised concerns from the beginning whether it would be ‘safe’ to consume irradiated food? However, after more than 100 years of research, the questions raised are resolved and the consumers accept irradiated food where it has become available together with an understandable explanation of the new technology. For example, in China very special items, as pickled chicken feet (irradiated), appear to have a certain market share. In the European Union the amount of irradiated food on the market place is marginal; however, varying drastically between Member States. More recent consumer studies are not available for the EU. The use of ionizing radiation in food processing remains still to be an under-estimated and under-exploited technology, in spite of its great potential [23].

4.4. Biopreservation
Natural compounds, such as essential oils, nisin, lysozyme, as well as natural or controlled microbiota, e.g. lactic acid bacteria (LAB) and their antimicrobial products such as lactic acid and bacteriocins, were investigated to extend the shelf life of meat/meat products and to obtain ‘green label’ products. For example, nisin is only commercially available bacteriocin and showed good antibacterial action in artificially contaminated pork and in combination with 2% sodium chloride an excellent anti-listerial effect in minced beef; pentocin 31-1 (produced by Lactobacillus pentosus 31-1 isolated from the traditional Chinese fermented Xuanwei ham) effectively inhibited volatile basic nitrogen (VBN) and suppressed the growth of indigenous microbiota, especially *Listeria* and *Pseudomonas*, in chilled pork storage [16].

4.5. High hydrostatic pressure (HHP)
The meat preservation process using HHP, a non-thermal technology, can effectively inactivate product-spoiling microorganisms and enzymes at low temperatures without changing dramatically the sensory or nutritional characteristics of the product; the tenderness is even improved, while the fresh meat color is slightly changed, after the HHP treatment. HHP is also a powerful tool to control risks associated with *Salmonella* and *Listeria monocytogenes* in raw or marinated meats [24]. Pressure processing is usually carried out in a steel cylinder containing a liquid pressure-transmitting medium, e.g. water, while the product is protected from direct contact by using sealed flexible packaging [16]. The recommended pressure/time combination for meat/meat products of 600–700 MPa for 2–5 minutes showed quick inactivation of *L. monocytogenes*, as well as other indigenous microbiota [25].

4.6. Active packaging
Active packaging is an innovative technology that allows the product and its environment to interact to extend the product shelf life and to ensure its microbial safety, while maintaining the quality of packed food. According to EU legislation, active packaging is a type of food packaging with an extra function, in addition to that of providing a protective barrier against external influence. It means that the packaging can absorb food- and environment-derived chemicals within the packaging surrounding the food or its releases substances into the food or the environment surrounding the food, e.g. preservatives, antioxidants, and flavorings [26]. There are three main types of active packaging which were developed so far: antimicrobial active packaging, antioxidant active packaging, carbon-dioxide emitting/generating packaging.

4.6.1. Antimicrobial active packaging
This is one of the most important concepts of active packaging of meat. There are four basic categories of antimicrobial packaging: (i) incorporation of antimicrobial substances into a pad inside the package, with aim to provide a slow release of antimicrobials, (ii) direct incorporation of the antimicrobial agents into the packaging film, by heat treatment (co-extrusion of packaging films with antimicrobials), so that antimicrobials can be gradually released from the packaging films to the packaging head space or food surface, (iii) coating of packaging with a matrix that acts as a carrier for antimicrobial agents, so to allow the release of antimicrobials onto the food surface through evaporation into the headspace (volatile substances) or migration into the food through diffusion (non-volatile substances), and (iv) use of polymers that have antimicrobial activity (e.g. chitosan, poly-l-lysine). In addition, a large number of antimicrobials were tested for inhibiting the growth of microorganisms in food, e.g. ethanol, carbon dioxide, silver ions, chlorine dioxide, antibiotics, bacteriocins, organic acids, essential oils, spices, plant extracts (rosemary), peptides, etc [27].

4.6.2. Antioxidant active packaging
High levels of oxygen in meat packaging can facilitate microbial growth, lipid oxidation, development of off-flavors and off-odors, color changes and nutritional losses. Therefore, control of oxygen level in meat packaging is important to prevent/retard the deterioration and spoilage of meat. Antioxidant active packaging systems can be classified into 2 groups: (i) independent antioxidant devices (sachets, pads or labels with oxygen scavengers – fine iron powder
and ferrous oxide), and (ii) antioxidant packaging materials (antioxidant active agent is incorporated into the walls of the packaging film (e.g. terpenoids from the propolis).

4.6.3. Carbon-dioxide emitting/generating packaging. Carbon dioxide has proven inhibitory effect for a range of aerobic bacteria and fungi via reduced oxygen level and through direct antimicrobial effect (by prolonging a lag phase and generation time during the logarithmic phase of microbial growth). Therefore, a CO₂ generating packaging system is a technique complementary to oxygen scavenging. The levels of CO₂ applied for meat and poultry preservation are relatively high (10-80%). For example 10-20% of CO₂ is needed for the inhibition of Pseudomonas, while 50% of CO₂ is necessary for control of proliferation of C. perfringens, C. botulinum and Listeria monocytogenes.

4.7. Wireless sensors
The manufacturers in the food industry frequently face the dilemma regarding the type of cold chain management in delivering products to retailers or end consumers, having to choose between frozen storage and cool storage (cooling, freezing, delivering and storage). Temperature is the main post-processing parameter in the determination of shelf-life in a cold chain of chilled and frozen food products. Frozen storage includes high-energy consumption for the preservation of food products, whereas cool storage involves the constant threat of bacterial-induced spoilage. Contemporary cold chain management encompasses temperature control and is focused on single logistic chain rather than serving multiple channels. In order to overcome the aforementioned deficiency, a time-temperature indicator (TTI) based cold-chain system is developed, which uses wireless sensors for collecting temperature data along the meat supply chain (from cold storage in slaughterhouse to retail) and implements the formulation of Critical Control Point (CCP) criteria throughout the entire delivery process. Under strict temperature monitoring, switching a number of products from frozen storage to cool storage seems to be feasible to improve the shortcomings associated with frozen storage (high-energy consumption, deterioration of taste, limited number of sale channels). Control charts are formulated for monitoring each point in the process. This approach is based on Internet of Things (IoT) architecture and international food standard (ISO 22000). IoT is a growing trend with a powerful influence in shaping the development of the information and communication technology (ICT) sector, e.g. radio frequency identification (RFID) tags, sensors, actuators, and even smart devices like mobile phones [28]. In practice, the IoT is expected to develop in areas such as wireless sensor networks with the aim of collecting contextual data. Further, a software approach to expanding web-based services using the capabilities of IoT (Web of Things, WoT) were recently developed. Lastly, a new business models in the food industry have been also developed: (i) cold chain home delivery service; (ii) convenience store (CVS) indirect delivery; (iii) CVS direct delivery; (iv) flight kitchen service [29].

4.8. Cold chain database (CCD)
The effective cold chain management can optimize freshness and safety of the product from farm/slaughterhouse up to the final consumer. The targeted data acquisition of time-temperature (t - T) profiles along the meat supply chain, as well as within the specific module of the cold chain stage (e.g. cold storage in slaughterhouse, transportation/delivery, retail) can serve as a valuable input for prediction of a product shelf-life status. From recently, a web-based platform was developed, within FRISBEE European project (http://frisbee-project.eu), for temperature conditions data collection throughout the chilled and frozen food supply chain. Data including all cold chain modules (industry, distributors, retailers and consumers), were collected to create the extensive database comprising more than 14,000 time-Temperature (t - T) profiles. Such platform can serve as a valuable Cold Chain Management tool. The Cold Chain Predictor (CCP) software based on the Cold Chain Database (CCD) allows calculation of product shelf-life status at different cold chain stages based on existing or user defined kinetic data. The developed tools offer the potential to run simulation scenarios based on real cold chain data and contribute to effective cold chain improvement and management [30].
5. Conclusion
The cold chain management in meat supply is of utmost importance for the maintenance of quality and safety of meat/meat products. The complexity of global meat supply chain, with frequently long distribution chains associated with transportation of the product within one country, from one to another country and from one to another continent, makes the solutions for the chilling and freezing regimes, as well as monitoring of time-temperature profiles, very important for the overall success in delivery of product which will be accepted by consumer for its freshness and safety levels. Although the importance of chilling and freezing regime effectiveness and temperature monitoring along the meat supply chain are well known, it remains a permanent challenge for the industry, distributors, retailers and consumers. From recently, there are several available options for control and management of the cold chain, such as chilled and frozen storage combinations, superchilling, ionizing radiation, biopreservation, high hydrostatic pressure (HHP), active packaging, wireless sensors, supported with the software-based cold chain database (CCD).

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